# Geology and Paleontology of the Lee Creek Mine, North Carolina, I

CLAYTON E. RAY

EDITOR

SMITHSONIAN CONTRIBUTIONS TO PALEOBIOLOGY • NUMBER 53

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# ABSTRACT

Ray, Clayton E., editor. Geology and Paleontology of the Lee Creek Mine, North Carolina, I. *Smithsonian Contributions to Paleobiology*, number 53, 529 pages, frontispiece, 95 figures, 101 plates, 8 tables, 1983.—This volume of papers on the geology and paleontology of the Lee Creek Mine is the first of three to be dedicated to the late Remington Kellogg, who initiated Smithsonian studies of the mine. It includes the first 14 papers, as well as a biography of Remington Kellogg by Frank C. Whitmore, Jr., and a prologue by Clayton E. Ray. This study places the Lee Creek Mine in the larger context of the history of Neogene geology and paleontology of the middle Atlantic Coastal Plain. Jack H. McLellan outlines the development and operation of Texasgulf's phosphate mine and manufacturing plant at Lee Creek, particularly as they relate to geological and paleontological studies. Thomas G. Gibson describes the regional patterns of Miocene-Pleistocene deposition in the Salisbury and Albemarle embayments of the central Atlantic Coastal Plain. On the basis of cluster analysis of 16 samples, including 149 taxa of ostracodes from fossiliferous beds above the Pungo River Formation, Joseph E. Hazel determines that the Yorktown Formation at the Lee Creek Mine is early Pliocene in age and the Croatan Formation spans the Plio-Pleistocene boundary. Among the ostracodes, 2 genera, 31 species, and one subspecies, are diagnosed as new. Walter H. Wheeler, Raymond B. Daniels, and Erling E. Gamble survey the post-Yorktown development in the region of the Neuse-Tar-Pamlico rivers. Primarily on the basis of auger holes, they begin with the Aurora paleoscarp marking the top of the Yorktown Formation, on which the organic-rich Small sequence (Croatan or James City Formation) was deposited, followed unconformably by the Pamlico morphostratigraphic unit; the inner edge of the Pamlico msu is associated with the Minnesott Ridge. H. Allen Curran and Patricia L. Parker divide the "Upper Shell" unit at the mine into three bivalve assemblage zones, probably formed through mass mortality in a series of local catastrophic events. Edward S. Belt, Robert W. Frey, and John S. Welch interpret Pleistocene deposition at the mine on the basis of biogenic and physical sedimentary structures, enabling them to recognize five major unconformities and four depositional sequences, indicative of a progradational shoreline under tectonically stable conditions. Their fourth depositional cycle includes a freshwater peat member thought to be of Sangamon interglacial age, on the basis of Donald R. Whitehead's pollen analysis. This analysis reveals high percentages of sedge and grass pollens, an absence of boreal indicators, tree pollen frequencies similar to those of interglacial deposits to the north and south, and general similarity of the fossil pollen spectrum to modern pollen assemblages of eastern North Carolina. Francis M. Hueber identifies the gymnospermous genera *Pinus*, *Juniperus*, and *Taxodium*, and tentatively the angiospermous genus *Gleditsia*, among the quartz-permineralized woods from the lower part of the Yorktown Formation at the mine; he also discusses the resin-like specimens, which are of unknown biological source and for which the stratigraphic source (Yorktown Formation, above the source of the woods) is known for only one specimen. William H. Abbott and John J. Ernissee report one silicoflagellate and two diatom assemblages (equivalent to Blow's zones N9 and N11) in a diatomaceous clay of the Pungo River Formation from two cores in Beaufort County; one new species of diatom is described. On the basis of 30 species of planktonic Foraminifera and a few radiometric dates, Thomas G. Gibson assigns ages from latest Oligocene through early Pleistocene to 10 stratigraphic units in the central Atlantic Coastal Plain; he describes 37 species and subspecies of benthic Foraminifera, of which 10 species and 2 subspecies are new. Scott W. Snyder, Lucy L. Mauger, and W.H. Akers assign an age of late-early to early-late Pliocene for a 15-meter section of the Yorktown Formation at the mine, based on 29 taxa of planktonic Foraminifera. Druid Wilson describes as a new genus and species of barnacle a puzzling fossil from inside the shell of the bivalve *Mercenaria* from the Croatan Formation. Porter M. Kier reports one species of echinoid from the Pungo River Formation, three from the Yorktown Formation, of which one is new, and two from the Croatan Formation. John E. Fitch and Robert J. Lavenberg record 45 taxa of teleost otoliths from the Yorktown Formation, representing 27 genera, of which 22 are new to the Pliocene of North America, and 6 are first fossil records.

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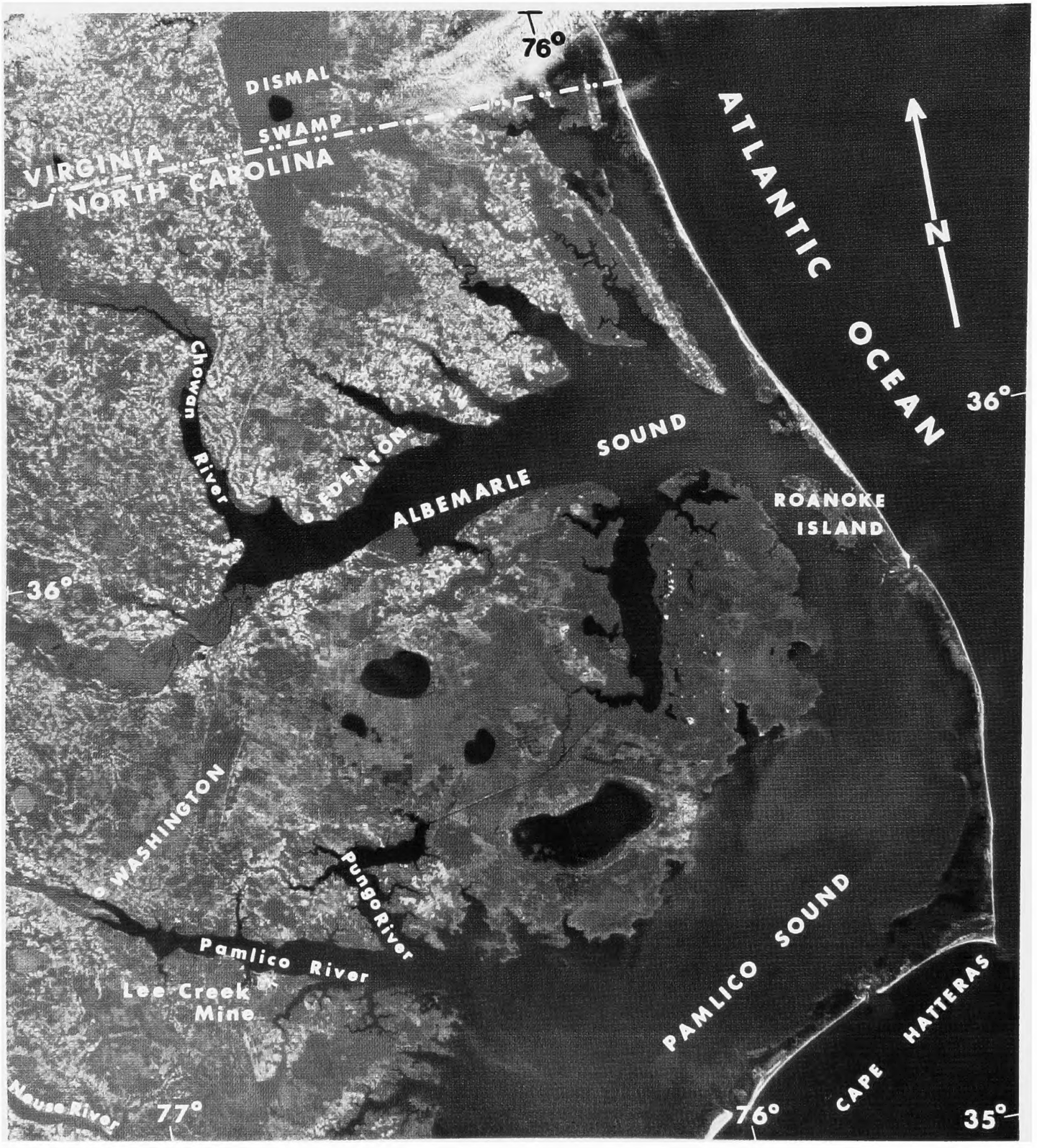
# Contents


| | Page |
|---|---|
| Prologue, by Clayton E. Ray | 1 |
| Remington Kellogg, 1892–1969, by Frank C. Whitmore, Jr. | 15 |
| Phosphate Mining at the Lee Creek Mine, by Jack H. McLellan | 25 |
| Stratigraphy of Miocene through Lower Pleistocene Strata of the United States Central Atlantic Coastal Plain, by Thomas G. Gibson | 35 |
| Age and Correlation of the Yorktown (Pliocene) and Croatan (Pliocene and Pleistocene) Formations at the Lee Creek Mine, by Joseph E. Hazel | 81 |
| The Post-Yorktown Stratigraphy and Geomorphology of the Neuse-Pamlico Area, Eastern North Carolina, by Walter H. Wheeler, Raymond B. Daniels, and Erling E. Gamble | 201 |
| Observations on the Paleoecology and Formation of the "Upper Shell" Unit, Lee Creek Mine, by H. Allen Curran and Patricia L. Parker | 219 |
| Pleistocene Coastal Marine and Estuarine Sequences, Lee Creek Mine, by Edward S. Belt, Robert W. Frey, and John S. Welch | 229 |
| Pollen Analysis of the Peat Member from the Lee Creek Mine, by Donald R. Whitehead | 265 |
| Fossil Woods and Resin-like Substances from the Lee Creek Mine, by Francis M. Hueber | 269 |
| Biostratigraphy and Paleoecology of a Diatomaceous Clay Unit in the Miocene Pungo River Formation of Beaufort County, North Carolina, by William H. Abbott and John J. Ernissee | 287 |
| Key Foraminifera from Upper Oligocene to Lower Pleistocene Strata of the Central Atlantic Coastal Plain, by Thomas G. Gibson | 355 |
| Planktonic Foraminifera and Biostratigraphy of the Yorktown Formation, Lee Creek Mine, by Scott W. Snyder, Lucy L. Mauger, and W.H. Akers | 455 |
| The Lee Creek Enigma, *Mclellania aenigma*, A New Taxon in Fossil Cirrhipedia, by Druid Wilson | 483 |
| Upper Cenozoic Echinoids from the Lee Creek Mine, by Porter M. Kier | 499 |
| Teleost Fish Otoliths from Lee Creek Mine, Aurora, North Carolina (Yorktown Formation: Pliocene), by John E. Fitch and Robert J. Lavenberg | 509 |

Dedicated to
Remington Kellogg
1892–1969




FRONTISPIECE.—Annotated false color composite image by NASA satellite (LANDSAT-3, image E-30116-15030), from altitude of approximately 915 km (568 mi), of part of southeastern Virginia and eastern North Carolina, 29 June 1978. Scale 1:1,000,000. Courtesy of United States Department of the Interior, U.S. Geological Survey.

# Geology and Paleontology of the Lee Creek Mine, North Carolina, I

## Prologue

*Clayton E. Ray*

What's past is prologue; what to come,
In yours and my discharge.

–SHAKESPEARE
*The Tempest*
Act II, Scene 1

John Brickell, M.D., lived and practiced medicine some 250 years ago in Edenton, North Carolina, on the outer Coastal Plain less than 50 miles (80.5 km) north of the Lee Creek (phosphate) Mine. With apologies for any license taken with his intent, with allowances for the accumulated knowledge and altered perspective of our age of specialization, and the concomitant reduction in our scope to one aspect of the natural history of one place in North Carolina, the following excerpt from his preface to *The Natural History of North-Carolina* (Brickell, 1737:iv–vi) seems admirably apropos to introduce the "Geology and Paleontology of the Lee Creek Mine, North Carolina."

*The Writings of many Learned Men may be seen on this Head, who after having search'd all the Records of Antiquity, shew much Erudiction, but nothing of certainty, concerning the Antient Affairs of* America. *I know the Memory of a Deluge is preserved amongst these people, but whether it is to be understood of the universal Flood, or the Inundation of some particular Provinces, I leave it to others to discourse upon, for I am willing to lay aside all manner of Conjectures of this Nature, having enough of Truth to treat of.*

. . . .

*But waveing these Discourses, we here present the World with a* Natural-History *of* North-Carolina, *it being a compendious Collection, of most things yet known in that part of the World; wherein I have laid down every thing with Impartiality and Truth, in the most plain and easie Terms, which indeed is the Duty of every Writer, and preferable to a more eloquent Stile, accompanied with many Falsities.*

*I have therefore endeavour'd in the following Sheets to give as faithful and exact Account of* Carolina, *as discoveries yet made will Authorize . . . .*

*But not to amuse the Reader any longer with Encomiums on* Carolina, *I refer them to my Description of that Country, and it's Inhabitants, which they will find in the following* Natural History, *in which I have been very exact; and for Methods sake, have ranged each Species of* Animals, Vegetables, *etc. under distinct and proper Heads.*

*A Collection of the Natural Curiosities of this spacious part of the World, will, I hope, not only give Satisfaction and Pleasure to each Reader, but likewise Profit, to all that are inclined to live in those Parts.*

*If these my Endeavours meet with this good success, I am thoroughly satisfied, having nothing more at Heart than to be in any Degree serviseable to the Publick; this being the principal Motive that induced me to undertake any Work of this Nature, (the Task being not only* Laborious *but* Difficult) *and not out of any Praise I expected from it.*

*Clayton E. Ray, Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560.*

*To conclude, Whatever Defects may be found in this Undertaking, we hope in time they will be supplied by the Labours and Industry of such as shall come after . . . and that their laudable Attempts may meet with just Encouragement, shall be my constant Wish and Desire.* [Italics in original.]

Although not of primary concern here, and not detracting materially from his eloquent preface, Brickell's apparently wholesale plagiarism must be acknowledged whenever his book is mentioned. The subject has been reviewed recently by Simpson and Simpson (1981).

The project of which the present publication is the culmination may fairly be said to have had its inception early in 1967 when Remington Kellogg received "a small collection of vertebrate fossils from the Lee Creek Mine" from Jack H. McLellan (letter of 2 March 1967). With Kellogg's encouragement, specimens continued to trickle into the National Museum of Natural History, where he began work on the fossil whales and enlisted others into looking at materials pertaining to their specialties. From the beginning through 1970, I had accumulated only a handful of seal bones (my favorite fossils) from the mine. The locality appeared to me to fit the all-too-familiar pattern for the Coastal Plain, that of yielding pinniped remains too sporadically to justify the expense of collecting trips. However, Jack McLellan visited the Museum on 10 December 1970, handed me a monachine seal temporal bone, viewed our meager collection, and assured me that it could be augmented readily through more vigorous pursuit on our part at the mine. With his encouragement and upon cessation of other duties, I visited the mine for the first time in August 1971. Frank Whitmore, Robert Purdy (Department of Paleobiology), and I joined McLellan for two days of collecting, the results of which were very satisfactory. For my part, the collection included enough pinniped fragments to persuade me that intensive effort well might yield collections unprecedented in variety, quantity, and novelty for the Atlantic Coastal Plain. On the same trip and equally important in retrospect was our visit with Peter J. Harmatuk of Bridgeton, North Carolina, a widely known, avid, and able fossil collector, who at this writing has contributed more vertebrate fossils to the National Collections than any other person.

The pattern for subsequent work was set and continues to the present. I have now made more than 50 visits to eastern North Carolina, typically of a few days each, in company with small groups from Washington. These groups generally consist of colleagues from the Smithsonian Institution and the U.S. Geological Survey, local students, and volunteers; but they have also included colleagues from as far away as England, Romania, and Japan. On a typical trip we rendezvous at the mine with faculty and students from interested schools, Texasgulf employees, amateurs from the area, and always with Peter Harmatuk. A part of every trip is devoted to other related activities, including prospecting other localities, examining institutional and private collections, assisting with the Aurora Fossil Museum, and participating in "fossil fairs." The continuing addition of specimens to the National Collections from non-Smithsonian sources (resulting from the contacts established on these trips) has been responsible, far more than our own collecting, for turning the initial trickle into a torrent; one product of this is that the vertebrate fauna of the Yorktown Formation is now one of the world's largest.

As this prospect quickened my interest, I began to educate myself in the geology and paleontology of the region and of the mine. I soon discovered a remarkable reservoir of knowledge and continuing interest on the part of colleagues at the Smithsonian and U.S. Geological Survey, including Thomas Gibson, who had published the basic paper on the geology of the mine in 1967, Blake Blackwelder, Joseph Hazel, Porter Kier, Lauck Ward, Alexander Wetmore, Frank Whitmore, and Druid Wilson, all of whose expertise exceeded, and whose interest antedated, my own. The combination of that resource, the ease with which other specialists were recruited across a broad range of relevant topics, and the burgeoning collections, culminated on 23 March 1972 with my proposing this publication project.

During much the same period, I had been casting about independently for a suitable means

of honoring Remington Kellogg in published form. It had seemed to me that such a tribute was long overdue from the institution that he had served since 1928 as curator and administrator, and as the giant of his era in marine mammalogy. A typical festschrift, consisting of papers united primarily by the relationship between the contributors and the honoree, seemed less attractive than something on a unified topic. The fact that Kellogg had chosen at retirement in 1962 to devote his energies to curation, research, and publication on fossil marine mammals of the Neogene of the Atlantic Coastal Plain, that he had been directly responsible for initiating Smithsonian research on the Lee Creek Mine, and that marine mammals are among the most conspicuous components of its fossil assemblage, all combined to suggest that this publication would constitute an appropriate and substantial tribute to his paleontological career in general and to his seminal role for Lee Creek in particular. Thus, this publication is dedicated respectfully to the memory of Remington Kellogg, and these volumes therefore begin with his biography and will conclude with a list and index of his publications.

Between these "end pieces" an attempt has been made to be as comprehensive as possible with regard to the geology and paleontology of Lee Creek Mine. For vertebrates it was feasible to be essentially exhaustive, and the third volume will be made up exclusively of those contributions, with the exception of a concluding chapter, comprising what is today popularly called an "overview," by Gibson and Whitmore, plus the appendices devoted to Kellogg. The first volume begins with a chapter about the mine and the mining itself, intended primarily to place our studies in context by revealing the opportunities created by the existence of the mine and at the same time the limitations imposed on collecting by the exigencies of mining. This is followed by chapters on the geology, concentrating on the regional setting, age, correlation, stratigraphy, paleoecology, and genesis of the deposits. Obviously, we have emphasized the aspects of geology most intimately related to paleontology and neglected or excluded many other potentially interesting aspects. These chapters are followed by three paleobotanical contributions, limited in number and scope by the availability of materials. The balance of the volume is devoted to invertebrates other than mollusks, plus a chapter on fish otoliths. The second volume is devoted exclusively to the mollusks, reflecting their abundance and importance. We have emphasized groups of special biostratigraphic value or special prominence or novelty at the mine, but have of necessity been governed also by the availability of appropriate specialists. The invertebrate fauna is so rich that, for practical purposes, the possibilities are unlimited. Obvious gaps in our coverage include the lack of comprehensive chapters on bryozoans and barnacles. These remain for future studies.

Although it is hoped that the whole publication will be found greater than the sum of its parts, each chapter is largely self-contained to the extent that its contents will be intelligible without reference to the whole, so that special interests can be satisfied through author's separates. This objective inevitably has resulted in some repetition, especially in the citation of literature.

Harking back to Brickell's expression of the writer's duty to lay down "*every thing with Impartiality and Truth, in the most plain and easie Terms*," this goal often may be approached best through pictures, and I have accordingly urged contributors to illustrate their topics generously. By this means I hope that these volumes will have been made more useful not only to specialists, but also to the host of serious, dedicated amateurs and students who are starved for reliable information, but who may not have command of the jargon that too often obscures the intrinsic interest of our subject.

Having outlined what we intended to achieve through publication of these volumes and how we have attempted to do it, there remains the question of why. Why North Carolina? Why the Lee Creek Mine? Why the Yorktown Formation? Perhaps a thumbnail sketch of the history of development of our knowledge of the Neogene of the middle Atlantic Coastal Plain will aid in answering these questions.

## Historical Perspective

The middle Atlantic Coastal Plain is especially significant to the early history of the sciences of North American geology and paleontology. Eastern North Carolina is particularly so, as it was the locale of the first efforts at permanent settlement by the English. The words and disciplines of geology and paleontology had yet to be defined, and the origin and significance of fossils would be debated for many decades (Ewan and Ewan, 1970:309–312; White, 1953a:137–138). However, explorers and colonists from the beginning had practical incentive to notice such matters because they were pertinent to their survival. Thomas Hariot (or Harriot), whom Sir Walter Raleigh sent to the Roanoke Island colony in 1585, recognized the essential distinction between the Coastal Plain and Piedmont, and probably also the nature of the fossil shell beds of the Coastal Plain (Hariot, 1590; White, 1952b:120; 1953a:136). The shell beds were of great importance as a source of lime for mortar (Bailey, 1938: 2). John Smith also recognized the distinction between the Piedmont and Coastal Plain, as evidenced by his map of 1612 (White, 1953b:125, 131), and William Strachey, first secretary of the colony at Jamestown, clearly characterized the fall line and demonstrated a surprisingly modern concept of the dynamics of the Coastal Plain (in Major, 1849:32):

> All the low land of South and North Virginia is conjectured to have bene naturally gayned out of the sea; for the sea, through his impetuous and vast revolution (who knowes not), savinge upon every coast, in some places wyns, and in other places looseth; and we find within the shoares of our rivers, whole bancks of oysters and scallopps, which lye unopened and thick together, as if there had bene their naturall bedd before the sea left them; likewise, the fashion of the earth is in smale rising mounts, which may well be supposed that the violence of the wynd hath cawsed, by dryving the light sand togither . . . .

He went on to comment upon the thin top soil and the lack of indurated rock in the subsurface, which he attributed to "want of tyme."[1]

The first explicit notice by Europeans of vertebrate fossils of the Coastal Plain Neogene was the entry of 3 August 1636 in Winthrop's journal (in Hosmer, 1908:185–186):

> Samuel Maverick, who had been in Virginia near twelve months, now returned . . . . It is very strange, what was related by him and many others, that, above sixty miles [97 km] up James River, they dig nowhere but they find the ground full of oyster shells, and fishes' bones, etc.; yea, he affirmed that he saw the bone of a whale taken out of the earth (where they digged for a well) eighteen feet [5.5 m] deep.

Simpson (1942:134; 1943:27) was curiously reluctant to accept these as bona fide fossils; but in fact from slightly above Hampton Roads to Richmond (well over 60 miles [97 km] up the James River) the Neogene strata are superlatively fossiliferous, most conspicuously in remains of whales (Baum and Wheeler, 1977) and mollusks (Blackwelder and Ward, 1976; Gardner, 1948). Thus, there is every reason to believe, and no reason to doubt, that Maverick saw fossils, most likely of Miocene, or, if the distance was exaggerated, at latest, early Pliocene (Yorktown), age.

Two scientist-clergymen lived on the Virginia Coastal Plain and made perceptive observations on its geology and fossils in the latter part of the seventeeth century, John Clayton from 1683 to 1686, and John Banister from 1678 to 1692. Clayton later lived in England and Ireland until 1725, and published rather extensively; Banister was shot (accidentally?) while exploring along the Roanoke River in 1692, and his enormous influence upon natural history in general and that of Virginia in particular has until recently not been widely appreciated. The analyzed and annotated works of each are now readily available in book form: Berkeley and Berkeley (1965) for Clayton, and Ewan and Ewan (1970) for Banister. In 1693 Clayton (Berkeley and Berkeley, 1965:57–59) commented at length on the extensive shell beds, speculated as to their derivation from living mollusks below sea level versus inorganic origin

[1] Although Strachey's writings were not published until much later, they were widely circulated in literary circles of London in the 1620s and probably were available to Shakespeare. They are thought to have provided at least part of the inspiration for "The Tempest," quoted at the beginning of this prologue (Kermode, 1958:xxv–xxxiv).

within the rock, and stated:

> Often, in the looser Banks of Shells and Earth, are found perfect Teeth petrefied, some whereof I have seen, could not be less than two or three Inches long, and above an Inch broad: Tho' they were not Maxilary Teeth, the part that one might suppose grew out of the Jaw, was polish'd and black, almost as Jett; the part which had been fasten'd in the Jaw and Gums, was brown, and not so shiningly polish'd, or smooth; if they were, as they seemed to be, really Teeth, I suppose, they must have been of Fishes [sharks?]. The Back-bone of a Whale, and as I remember, they told me of some of the Ribs, were digg'd out of the side of a Hill, several Yards deep in the Ground, about four Miles distant from James-Town, and the River. Mr. Banister, a Gentleman pretty curious in those things, shew'd me [in 1686; Ewan and Ewan, 1970:xx, 58] likewise the Joynt of a Whale's Back-bone, and several Teeth, some whereof, he said, were found in Hills beyond the Falls of James River . . . .

At least some of the teeth undoubtedly represented Pleistocene mammals from west of the Coastal Plain, as various authors have supposed (Ewan and Ewan, 1970:331), but the whale vertebra and probably some of the (shark?) teeth must have been local, especially in view of Banister's own writings, for example (in Ewan and Ewan, 1970:332):

> 20 or 30 miles [32 or 48 km] up ye freshes of James River I found great variety of petrified oysters, scallops, bones &c. among them these strange stones, which I am not so good an ichthyologist to assign to what fish or fishes they might belong, if they were ever reall teeth. & higher up yet within 12 miles [19 km] of ye falls, about 1/2 mile [0.8 km] from the River in a gully on ye side of a hill, near a small creek 40 or 50 foot [12 or 15 m] perpendicular above ye flowing of ye tyde, I met with another of these teeth, like ye first but smaller, its armature of ye colour of cinammon, the rest liver-colour'd, & with it ye like variety of ye sea shells &c. I am informed to[o] that divers of ye high banks downwards (tho out of ye tydes reach as it now flows) are compos'd almost wholly of them, & that they are found there also in many places remote from ye river.

He went on to debate whether the fossils indicate former presence of the sea or direct formation in the rock, and he made drawings of a shark tooth, fossil invertebrates, and a sting ray spine (Ewan and Ewan, 1970, figs. 65, 67, 68). There is no doubt that Banister aided and influenced Martin Lister, and his drawings, notes, and specimens may well have provided the basis for Lister's (1685–1692; in Ewan and Ewan, 1970:315) widely heralded first published illustrations and descriptions of American fossils (in Ward and Blackwelder, 1975:3; Wilson, in prep.; Ewan and Ewan, 1970:312 et sqq.).

In his widely known work, Mark Catesby (1731:second vii) made the following comments on Neogene fossils of the Coastal Plain:

> There is no Part of the Globe where the Signs of a Deluge more evidently appears than in many Parts of the Northern Continent of *America*, which, though I could illustrate in many instances, let this one suffice. Mr. *Woodward*, at his Plantation in *Virginia*, above an Hundred Miles [161 km] from the Sea, towards the Sources of *Rappahannock* River, in digging a Well about seventy Feet [21 m] deep, to find a Spring, discovered at that Depth a Bed of the *Glossopetrae* [shark teeth], one of which was sent me. All Parts of *Virginia*, at the Distance of Sixty Miles [96.6 km], or more, abound in Fossil Shells of various Kinds, which in *Stratums* lie imbedded a great Depth in the Earth, in the Banks of Rivers and other Places, among which are frequently found the *Vertibras*, and other Bones of Sea Animals.

Lewis Evans (in Gipson, 1939; White, 1952a) was a very perceptive mapmaker of the middle 1700s who understood the nature of fossils, and delineated physiographic features, including the Coastal Plain and the fall line.

One of the great unknowables of American geology is the impact that the works of Johann David Schöpf would have had, had they been widely available in English to his contemporaries and immediate successors. His American travels, published in 1788 in German and not translated until 1911, remained rare until reprinted recently (Morrison, 1968), and his American geology, published in 1787, was not published in translation until 1972 (Spieker, 1972). Although now widely appreciated and acknowledged as an accurate observer and clear thinker in a time of uncertainty in geology, his works had no known impact in America for well over a century after their publication, which is to say not until long after the progress of the science had passed them by. Schöpf was in America from 4 June 1777 to 29 March 1784, during most of which time he was closely limited to the vicinity of New York and Philadelphia as surgeon to German troops in service to the British. On 22 July 1783, however, he left New York on his generally southward

travels that took him through the Coastal Plain of Virginia and North Carolina. He went out of his way to visit Yorktown (Morrison, 1968 (2):82–85), because of its significance as a "remarkable theatre of a decisive military event, as well as by the wish to examine the great shell-banks there, which are an object of curiosity to every stranger"; he discussed in enthusiastic terms a shell bed exposed in a mill race halfway between Williamsburg and Yorktown, noting as well "large bone-fragments, presumably of whales." Continuing southward, he noted shell banks also on the Tar River (Morrison, 1968(2):125), where he had already mentioned that proboscidean remains had been found (Morrison, 1968(1):269). In his geological treatise (in Spieker, 1972:48–49) Schöpf made more generalized statements about the distribution of the shell bed and mentioned "sharks' teeth, whale and other bones" as well.

Intimations of things to come in the new republic, even without benefit of Schöpf's insights, are provided by three sets of observations published before 1800. Their significance lies not in their originality but in their suggesting fairly widespread geological sophistication and the development of a society in which homegrown investigations of rather narrow esoteric topics could find outlet in American journals. The first of these, published in 1785, by the American Academy of Arts and Sciences in Boston, consists of a detailed description of the geologic section in the vicinity of Yorktown, Virginia. This publication is based upon observations made by a revolutionary general, Benjamin Lincoln, during the last weeks of the war, prior to the British surrender at Yorktown on 19 October 1781.

In June 1786, the Reverend Samuel West with Dr. William Baylies and others visited Gay Head, Martha's Vineyard, the northernmost emergent outlier of the Coastal Plain. Both West (1793) and Baylies (1793) published accounts of the visit. West had been "appointed by the Academy to be a committee, to examine the mineral production of Gay Head." According to West (1793:148), "the inhabitants presented us with a petrified bone, said to be one of the vertebrae of the whale, which they told us they found in the cliff: It is very heavy, owing, I apprehend, to a metallick impregnation. They also brought us two shell fish, which were petrified: These were taken out of the cliff." Baylies (1793:155) added: "The bones of whales, sharks' teeth, and petrified shellfish, are frequently picked up, scattered up and down the cliff, at a considerable distance above the surface of the water."

The third example is that of Benjamin Henry Latrobe, a prominent architect and engineer who directed construction of the U.S. Capitol and the White House, and designed many other buildings, as well as municipal water systems and canals (Lintner and Stapleton, 1979). He made practical use of geology in his profession, as reflected by the section through Richmond, Virginia, in his journal for 4 May 1798 in connection with construction of the penitentiary of his design (Lintner and Stapleton, 1979, fig. 1). On the same pages he recorded a detailed log to a depth of 71 feet [21.6 m] of the well at the penitentiary, and in 1799 published commentary in the *Transactions of the American Philosophical Society* on

> the fossil teeth and bones, which accompany this memoir,* and which with many hundred more, were dug out of a well at Richmond, from the depth of 71 feet . . . .
>
> * The teeth appear to be those of a shark. They are highly enamelled and extremely sharp: their roots are perfectly sound and entire, and the minute and almost transparent jags of many of them are as perfect as the rest. They are found in every well, dug in or near Richmond, to a sufficient depth; and, *as I am informed*, in every deep well for many miles below the city. The stratum in which they lie consists of highly sulphurated blue clay, abounding in pyrites, and which has the appearance of having been mud. They were first discovered in the beds of rivulets, which had worn their channels to the depth of this stratum; and obtained the name of *Indian Dart-points*, in the same manner, as the immense oysterbeds, which have been quitted by the ocean, are vulgarly called *Indian* oyster-banks.
>
> The bones were dug from the same stratum. Among them are two out of six bones, which formed a *paw* of some animal unknown to me. Many very sound vertebrae of fish, and a remarkably perfect thigh bone of a large bird have been in my possession.

The paper is accompanied by well-executed drawings (reproduced by Lintner and Stapleton,

1979, fig. 2) of four shark teeth, the two recovered bones, and an outline of a third bone. The bones are indeed those of the paw, or forelimb, of a small porpoise, well known in the Miocene deposits of the Coastal Plain, including Richmond (Ray, 1976:10). The two recovered are the humerus and ulna of a mature individual, and the bone outlined is the radius. The reference to the fossil bird bone may be the first for the Coastal Plain.

It is interesting to note that on 16 April 1818, Latrobe advised on the proposed construction of a canal in North Carolina without going there, based on extrapolation from his knowledge of geology from New York to the Roanoke River (Lintner and Stapleton, 1979:112). It is equally interesting, and perhaps not entirely coincidental, that in April of the following year, Latrobe's fellow surveyor and engineer, William Smith (also the founder of stratigraphic paleontology), seriously considered an offer to come to North Carolina as an advisory engineer; he declined, however, and by June found himself instead in debtor's prison (Eyles, 1969:157). Might the subsequent history of geology in the Coastal Plain of North Carolina have been significantly altered had he decided otherwise? Probably the approaches to both Latrobe and Smith stemmed from the Board of Internal Improvements of the state, which concerned itself with surveys of rivers, and for railroads, turnpikes, canals, and swamp drainage (Merrill, 1920:363).

Samuel Latham Mitchill (1818), in what may be regarded as one of the last major publications of the classical period, reviewed fossil records in North America. Among many others he noted several of interest for the Neogene of the middle Atlantic Coastal Plain, including some occurrences of fossil wood and the following of vertebrates:

> I remember, that petrified bones, apparently of a whale, were brought from the shore of Chesapeake Bay, near the place where the river Patuxent enters it, to the City of Washington, by Mr. O'Neale. (Mitchill, 1818:394)
>
> Shark's teeth, or glosso-petrae, are often raised on digging wells, further down the [Potomac] river, as at Diggas's point, for example. (Mitchill, 1818:396)
>
> Mr. Chevallié brought me, from Richmond, entire triangular teeth, apparently of sharks, and pieces of bones, probably of whales, dug from the depth of between sixty and one hundred feet [18 and 30 m], in the city of Richmond .... in the neighborhood of Williamsburgh, in 1802, a considerable portion of a whale's skeleton was discovered. It was about four or five feet [1.2 or 1.5 m] under ground; two miles [3.2 km] distant from the shore of James' river, and fifty [80.5 km] from the Atlantic ocean. Among other parts were fragments of the ribs, and all the vertebrae regularly arranged, and very little impaired as to its figure. (Mitchill, 1818:397)
>
> At a place called Fishing creek, 150 miles [241 km] from the sea coast, and almost four [6.4 km] from Tarborough, in digging some little depth, they found a part of the skeleton of a whale, with sea shells in abundance .... The skeleton of another whale, together with a petrified portion of a shark's jaw with teeth, has been found at a place called Williamstown, more than 100 miles [161 km] from the sea coast.
>
> About a year ago, the skeleton of a huge animal was found on the bank of the Meherrin river, near Murfreesborough. It was dug out of a hill, distant sixty miles [97 km] from the ocean. Capt. Neville and Dr. Fowler, who visited the spot, gathered the scattered vertebrae which the negroes had thrown out, and laid them in a row thirty-six feet [11 m] in length. If to this the head and tail be added, the creature must have been perhaps fifty feet [80.5 m] or more in length. The former of these gentlemen enriched my collection with two of the teeth and a joint of the back bone that he brought away. The teeth weigh sixteen ounces [0.45 kg] each. They are covered with an ash-coloured enamel, except at the roots where they were fastened in the jaws. Their figure is triangular, the sides towards the apex measuring six inches [15.24 cm] each, and the base four inches and a half [10.16 cm] across. The joint of the back is not cartilaginous, but actually bony. It is in some degree petrified, and weighs twelve pounds and a half [5.7 kg]. It, in all likelihood, belonged to a shark or a sea-serpent. (Mitchill, 1818:400–401)

Although the distances from the sea are exaggerated, the records of large whales from the vicinity of Tarboro and Williamstown probably apply to mysticetes preserved in the Yorktown Formation; however, the "petrified portion of a shark's jaw with teeth" is more suggestive of an archaeocete, which could only have come from the Eocene Castle Hayne Formation. Similarly, if the large triangular teeth from near Murfreesboro were indeed from the same animal as the skeleton, they could scarcely represent any animal

other than a large archaeocete. However, it seems unlikely that the Castle Hayne Formation would have been penetrated in that area, at that time, but likely that the skeleton was that of a mysticete and the teeth those of *Carcharodon* associated in the same Neogene strata.

These early investigations and reports were an essential prelude to the subsequent development of geology. For example, the creation by Benjamin Silliman of the *American Journal of Science*, which was the first American periodical of broad scope devoted primarily to geology, could scarcely have come into being earlier than 1818, because the ground rules of the science were only then being laid. Without the preceding primitive efforts as a substrate, there would have been neither authors nor audience for such a journal.

Beginning in the 1820s and continuing apace through the next two decades, American science underwent rapid expansion and developing professionalism, characterized in geology by the first official state geological surveys and in paleontology by the development of increasingly standardized procedures, including adoption of Linnaean systematics. It is neither feasible nor necessary to attempt to chronicle the burgeoning developments from this time onward, for the history and literature have been thoroughly covered in standard sources such as Darton (1896), Gregory et al. (1973, and volumes cited therein, by Camp et al.), Hay (1902), Hazen and Hazen (1980), Merrill (1906, 1920, 1924), Nickles (1923, 1924), and Schneer (1979). For the individual states the literature for Maryland is covered by Clark (1897), Mathews (1897), and Shattuck (1904); for Virginia, Clark and Miller (1912), and Roberts (1942); for North Carolina, Laney and Wood (1909), Clark, et al. (1912), and Stuckey (1965), and Riggs and O'Connor (1975).

The first official state geological survey of North Carolina was conducted by Denison Olmsted and Elisha Mitchell, 1824–1827, and may be regarded with some justification as the first for any state (Back, 1959; Merrill, 1920:363). Following closely were the surveys of Julius Timoleon Ducatel for Maryland, 1833–1842, and of William Barton Rogers for Virginia, 1835–1841 (Aldrich and Leviton, 1982). These surveys, all including some work on the Coastal Plain, were followed by others in the nineteenth century. In North Carolina surveys were made by Ebenezer Emmons in the 1850s (Johnson, 1982) and Washington Caruthers Kerr from the Civil War to 1885, and were supplemented by other work, conducted in part by the same geologists but also by others in increasing numbers. Serving as the capstone for nineteenth century efforts and as the foundation for all subsequent work on middle Atlantic Coastal Plain geology are the unifying, comprehensive publications by William Bullock Clark and his coworkers: for Maryland, Clark, Shattuck, and Dall, 1904: for Virginia, Clark and Miller, 1912; for North Carolina, Clark et al., 1912.

By 1830, Timothy Conrad, Samuel G. Morton, and a few others had begun the work that would result in monumental publications (e.g., Conrad, 1830, 1842, and in Dall, 1893; Morton, 1829, 1834) in systematic and stratigraphic paleontology, based almost entirely on invertebrates, although Morton also published on vertebrates, mostly of Cretaceous age. Richard Harlan, characterized as America's first professional vertebrate paleontologist (Simpson, 1942:161), began work in the 1820s, and in 1842 he published the first formal description of a fossil cetacean from the Neogene of the Coastal Plain, *Delphinus calvertensis* (later transferred to *Lophocetus*). Work on the fabulously rich invertebrate faunas by numerous subsequent researchers, among whom Julia Gardner (1948) may be mentioned as a leading practitioner, continues as reflected in the present volumes. For the vertebrates, Harlan's small beginning was followed by the extensive work, primarily on cetaceans, of Joseph Leidy, Edward Drinker Cope, Frederick William True, and above all Remington Kellogg. Perusal of their many publications on fossil vertebrates of the Chesapeake Series (Hay, 1902; Gregory et al., 1973; Knapp, in prep.) reveals very little on the Yorktown Formation and relatively little on North Carolina. The reasons are readily apparent; in spite of the occasional notice of large whale skeletons since early colonial times and the

superabundance of invertebrates, natural exposures have produced an unreliable crop of vertebrate material. Of that, very little of adequate quality reached the hands of researchers, as compared, for example, to the abundance of good specimens from the Calvert Formation of Maryland. Beds of Calvert age are unknown in outcrop in North Carolina.

All of this changed dramatically and suddenly with the opening of the Lee Creek Mine, which provided the first exposure in North Carolina of deposits in part equivalent to the Calvert Formation (the Pungo River Formation) and continuously renewed access to the Yorktown Formation. With respect to vertebrates, publication of the present volumes will transform the Yorktown Formation from virtual terra incognita to one of the richest known deposits.

## Conclusion

Much is made these days of a priori research design, of deciding first on a significant problem to be pursued, then going forth to select an appropriate vehicle to carry the scholar to his goal. For this reason it is argued that museums should not be cluttered up with collections unless there is a specific proximate purpose in mind. Although there is some justification for this reaction to traditional methods ("stamp collecting" to some), it is all too characteristic of our culture to lurch from one extreme to another, to lose interest in and even discontinue an activity because it is not new. In fact, however, the great work of discovering and deciphering the record of life on earth has barely begun. If there is a loss of confidence in museum science, if it collapses, it will not be through indifference or hostility from without (the National Museum of Natural History had 5,464,229 visitors in 1979), but by implosion, when museums are no longer populated by museum scientists. A colleague recently stated that a good museum scientist should have a "subclinical obsession" with collections, seemingly more appropriate than a fear of pursuing our profession too vigorously. There will be no lack of external forces to set practical limits to growth of collections, not the least of which is availability in the case of vertebrate fossils. A strong element of self-deception creeps in if we deny the often dominant opportunistic factor in our research design. After his more than 40 years of productive research on marine mammals of the Atlantic Coastal Plain that had yielded virtually nothing from the Yorktown Formation or from North Carolina, Remington Kellogg understood the importance of capitalizing on the opportunity presented.

Before the Lee Creek Mine existed, there was no possible means to learn about the Pungo River Formation except through limited access by drilling, and there was no prospect of significant extension of knowledge of vertebrates of the Yorktown Formation. Although to my mind, the traditional goal of increasing and diffusing knowledge of earth history is adequate justification for the study of the geology and paleontology of any place, it may be pointed out also that only through multiplication of richly documented points in space and time will we be able to perceive general patterns of distribution, evolution, and correlation. It is hoped, therefore, that these volumes will demonstrate the utility of being ready to exploit opportunities as they arise. There can be no doubt that we could have done more and better. There remains a great need for better stratigraphic control, more comprehensive taxonomic coverage, and better quality materials, especially of the vertebrates, but these needs can be satisfied only by future work, most especially by more extensive and leisurely access to sections in place, perhaps through setting aside a research reserve. That, however, remains for another time and possibly for other hands. I can only refer again to John Brickell's felicitous concluding words quoted at the beginning of this prologue, "*that their laudable Attempts may meet with just Encouragement shall be my constant Wish and Desire.*"

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I have saved until last my expression of thanks to Peter J. Harmatuk, for he is truly in a class by himself. At the end of 1975 he retired early, at financial loss, from a successful career because it interfered with his paleontological field work. Yet he is the antithesis of the monomaniac misfit hiding an inadequate personality among fossils, for he is a leader in his community and pursues other, nonpaleontological interests with similar vigor. I would regard his acquaintance as one of life's rare pleasures had he never collected a fossil. However, that is far from the reality. In the course of hundreds of collecting days at the Lee Creek Mine, to say nothing of numerous other localities in eastern North and South Carolina, he has collected with unflagging enthusiasm more fossils of more kinds for science than anyone who has

ever worked the middle Atlantic Coastal Plain. In many cases he has been the first to bring a locality to the attention of paleontologists, to influence other collectors toward a scientific orientation, to recognize an unusual stratigraphic occurrence, or to discover specimens unprecedented in kind, quantity, or quality. More than once his tenacious curiosity has forced me to pay attention at length to something of interest previously brushed aside. His rare combination of self-effacing humility and constitutional inability to accept glib answers based on faulty reasoning from vested authority has made our association a source of continuing satisfaction and education for me. If one ever needed a reminder that paleontology traditionally has been and remains largely a field science, the enjoyment and advancement of which is open to Everyman to the extent of his ability, effort, and interest, Pete Harmatuk provides irrefutable proof. With little of the externally conferred advantages of education, opportunity, and funding, his contributions demonstrate that there is no substitute for innate intellect and good character.

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# Remington Kellogg
# 1892–1969

*Frank C. Whitmore, Jr.*

Remington Kellogg, retired Assistant Secretary of the Smithsonian Institution and former Director of the United States National Museum, died of a heart attack on 8 May 1969, in his seventy-seventh year, at his home in Washington, D.C. He had been recuperating from a broken pelvis suffered in a fall on the ice the previous January. Except for that period, he had been constantly and productively engaged in research at the National Museum for more than 49 years. To him retirement, which came in 1962, brought welcome relief from administrative duties and an opportunity to intensify his study of fossil marine mammals. The years 1962 to 1969 were among his most productive.

Arthur Remington Kellogg, as he was christened (he early dropped "Arthur" from his name), was born in Davenport, Iowa, on 5 October 1892, the son of Clara Louise (Martin) and Rolla Remington Kellogg. He was descended from colonial stock on both sides of the family. One ancestor, Sergeant Joseph Kellogg, came from England in 1651, settling first in Farmington, Connecticut, and finally at Hadley, Massachusetts, in 1661. Sergeant Kellogg helped to defeat the Connecticut Indian tribes at Turner's Falls, Masschusetts, in 1676.

Kellogg's paternal grandfather taught Latin and Greek in high school in Davenport, Iowa. His father was a printer, who at one time or another was owner of several printing shops. Remington's mother was a school teacher before her marriage. The Kelloggs moved to Kansas City, Missouri, when Remington was 6 years old. Of his early years Dr. Kellogg said:

> I do not recall that I disliked any particular study. Westport High School in Kansas City was considered at the time to be an academic rather than a manual training high school. The courses given were in accordance with a regular schedule of four years of English, history, mathematics, science, and Latin . . . .
>
> From the fourth grade onward while attending public grade and high schools most of my spare time outside of school hours was devoted to studying wild life in the nearby woods, and by the time I graduated from grade school I had prepared a small collection of mounted birds and mammals.

Before completing his high school studies, Kellogg had decided to attend a university where there were natural history collections. This interest led him to the University of Kansas, the training ground for many famous naturalists. Remington found it necessary to find employment as a salesman in a dry goods store, as a worker in the smoke house of a packing plant, and as a cement worker on a construction crew in order to save enough money for college. In his first years at the university he cooked his own meals and delivered papers. He sold trunks as a traveling salesman during the summer after his freshman year. At the university he concentrated first in entomology; later he changed his field to mammals. From 1913 to 1916 he was a taxonomic assistant for mammals under Charles D. Bunker, curator of birds and mammals in the Museum of Natural History at the university. His first paper,

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Remington Kellogg
5 October 1892–8 May 1969
(Photograph, 1963)

published in 1914, resulted from this museum work. Bunker took Kellogg to his cabin where he instructed him in skinning and preserving vertebrate specimens. Upon the death of an instructor during his senior year, Kellogg helped give a class in ornithology. He received his A.B. in January 1915 and his M.A. in 1916.

In Kellogg's freshman year there began a lifelong friendship with Alexander Wetmore. In 1911, Wetmore joined the Bureau of Biological Survey, U.S. Department of Agriculture, and helped Kellogg in getting summer jobs with the Survey, conducting field surveys of plant and animal life in the West. The two men worked closely together for many years in the Smithsonian Institution, first as curators and later in administrative positions, when Wetmore was Secretary of the Smithsonian and Kellogg, Director of the Smithsonian's United States National Museum. Another admired friend of undergraduate days was Edward A. Preble of the Biological Survey. Preble was an editor and frequent contributor to the magazine *Nature*, then published in Washington, D.C. Among many wildlife monographs he published a study of the fur seals of the Pribilof Islands.

Immediately after graduation, in the winter of 1915–1916, Kellogg worked for the Biological Survey in southeastern Kansas, and, during the following summer, in North Dakota. Of this assignment he said,

> I remember the first year I went out to Wahpeton, North Dakota, the first day the chief of the survey took me out and we walked all over the area. Then he said, "Well, I'm leaving. You know all about it." From then on I was alone. I had to cover everything—plants and animals—and write a report. It didn't faze me a bit—I guess I didn't know any better.

While at the University of Kansas, Kellogg made his first acquaintance with marine mammals in the form of skeletons of white whale, porpoise, walrus, and seal. In the fall of 1915, at the end of his summer's fieldwork, the Biological Survey paid his way to Washington, D.C. He made a tour of museums in the eastern United States, which undoubtedly gave him further opportunity to examine whales, pinnipeds, and sirenians. At about this time he made his decision to study the evolution of marine mammals, and in the fall of 1916, he entered the University of California at Berkeley to concentrate in zoology. At Berkeley, Kellogg met several men who became lifelong friends and in various ways influenced his professional growth. Perhaps the most revered of these was David Starr Jordan, ichthyologist and president of Stanford. Joseph Grinnell, Director of the Museum of Vertebrate Zoology at the University of California, stimulated Kellogg's interest in ornithology. Chester Stock, a fellow graduate student and later Professor of Vertebrate Paleontology at California Institute of Technology, shared many hours of discussion of evolution.

The most lasting influence resulting from the Berkeley years was that of John C. Merriam. Kellogg was given a teaching fellowship and was invited by Merriam to study the fossil record of the seals, sea lions, and walruses whose remains had been found in Pacific Coast Tertiary formations. This project resulted in Kellogg's first important papers on marine mammals (1921 and 1922a), both dealing with fossil pinnipeds. With the thoroughness, coupled with deceptively modest titles, that was to characterize his published work throughout his career, the second of these (entitled "Pinnipeds from Miocene and Pleistocene Deposits of California") incorporated a critical review of the literature of fossil pinnipeds of the world. This work remains the basis upon which modern research on fossil pinnipeds stands.

In the summer of 1917, Kellogg again did fieldwork for the Biological Survey. He went to Montana and then to California, where he studied the *Microtus californicus* group of meadow mice. A monograph resulting from this work was published in 1918.

Graduate work was interrupted by service in World War I. On 11 December 1917, Kellogg enlisted in the 20th Engineer Battalion at San Francisco, and on 19 February 1918, he sailed from Hoboken for France. By a stroke of good luck, for a naturalist, Kellogg was transferred in May 1918 to the Central Medical Department Laboratory at Dijon, where he was promoted to

sergeant and found himself under the command of Major E.A. Goldman, one of the last of the general field naturalists. One of their major assignments was rat control in the trenches and at the base ports. During his service in France, Kellogg observed and collected birds and small mammals, and sent collections to Joseph Grinnell at Berkeley and Charles D. Bunker at the University of Kansas. His notebook contains almost daily observations from 17 November 1918 to 23 February 1919. The climax of this period was a motor trip that he took between 29 January and 23 February with Major Goldman and Lieutenant A.C. Chandler from Dijon to Toul and "such other places in depts. of Meurthe-et-Moselle, Meuse, and Ardennes as is necessary to carry out instructions of Chief Surgeon, in connection with preparation of medical history of war." During the period of this reconnaissance, his notebook lists 30 species of birds and five of small mammals.

Upon his return to Berkeley, Kellogg gave a talk to the Northern Division of the Cooper Ornithological Club entitled "Experiences with Birds of France," and in 1919, he published, with Francis Harper, who had also been in the Army in France, a Christmas day bird census made at Is-sur-Tille in the Department of Côte d'Or, where the Army Medical Laboratory was situated.

In June, Kellogg returned to the United States. He was discharged from the Army at Newport News, Virginia, on 2 July 1919 and returned immediately to Berkeley to complete the residence requirements for his doctorate. He transferred from zoology to vertebrate paleontology under Merriam, resumed his teaching fellowship for a semester, and then, on 1 January 1920, was appointed assistant biologist in the Biological Survey, with headquarters in Washington, D.C.

While at Berkeley, Kellogg had met a fellow student, Marguerite E. Henrich, a native Californian. They were married in Berkeley on 21 December 1920 and set up their home in Washington, where, with many interludes of travel, they were to spend their entire married life.

For the next eight years, Kellogg performed various assignments in field and laboratory for the Biological Survey. He was well suited for such work by inclination and training and by a tremendously retentive memory and systematic use of the literature. All his life he was an inveterate reader and maker of reference cards with annotations, filed taxonomically by subject and by author.

Much of Kellogg's work with the Biological Survey had to do with the feeding habits of hawks and owls, which entailed both field observation and the examination of hundreds of pellets. Observations were also made of the feeding habits of diving ducks, which were suspected of depleting trout populations. In a travel authorization issued in 1920, Kellogg is referred to as "Assistant in Economic Ornithology."

Between 1920 and 1927, a great deal of time was devoted to the drudgery of examining pellets and stomach contents from owls and hawks, and the principal results were published in 1926, 1928(b), and 1932(b). Concurrently with his ornithological work, Kellogg spent much time studying toads, mainly museum specimens, including examination of stomach contents. In 1922, he published a Biological Survey Circular (1922c), one of a number that he wrote, on the toad, and during that year he planned a revision of the toads of North and Middle America. The entire project was not completed, but it did result in an important monograph on Mexican tailless amphibians in the United States National Museum (1932a).

Another dietary study was made of alligators. In the 1920s, there was a controversy over whether alligators should be protected from indiscriminate hunting. Kellogg was given the task of finding out how predatory they actually were, and in 1929 he published a Technical Bulletin of the U.S. Department of Agriculture, "The Habits and Economic Importance of Alligators."

At about the time Kellogg joined the Biological Survey, his professor, John C. Merriam, was appointed president of the Carnegie Institution of Washington. Merriam arranged an appointment for Kellogg as a research associate of the Carnegie

Institution, a position which he held from 1921 to 1943. Annual research grants from the institution helped Kellogg to carry on research on marine mammals concurrently with his extensive projects for the Biological Survey. It was decided that an investigation of the earliest known predecessors of the typical cetaceans, the Archaeoceti, found in older Tertiary rocks, would be supported by a grant. In October 1929, Kellogg went to Choctaw and Washington counties in Alabama to collect zeuglodont material to supplement the archaeocete collections in the United States National Museum. The monograph resulting from this study, "A Review of the Archaeoceti," published in 1936, is a landmark in cetology.

Merriam's increased administrative duties left him little time for paleontology, and he encouraged Kellogg to begin a project that Merriam had long had in mind: the study of the marine mammals of the Calvert Cliffs in Maryland. Beginning in the early 1920s, Kellogg devoted many weekends to collecting, adding significantly to the collections of his predecessors, William Palmer and Frederick W. True. By the time of Kellogg's death, the collection of fossil marine mammals in the National Museum collections was probably the best in the world.

The most fascinating aspect of marine mammals is the way in which existing mammalian organs have been modified for life in the sea. Kellogg decided to make this theme the basis for his doctoral thesis, which, because of the war and other matters, had yet to be written. Using the literature, but also drawing heavily on his own original studies, he wrote "The History of Whales: Their Adaptation to Life in the Water" (1928a), for which he was awarded his doctorate by the University of California. This paper is still the best summary of the subject.

In 1928, Kellogg had transferred to the United States National Museum of the Smithsonian Institution as assistant curator of mammals under Gerritt S. Miller, Jr., and became curator in 1941. With his transfer to the Smithsonian, he was able to devote more time to the study of marine mammals. He has described the course of his research as follows (1968b:283–284):

> In the earlier stages the marine mammal studies were largely descriptive but as they progressed the importance of fossil cetaceans for geological correlation became apparent. As a collateral investigation, the recorded occurrences of migrating whales in the several oceans were collated. These observations confirmed the belief, more recently supported by whale marking, that the Recent whalebone whales make seasonal migrations from tropical calving grounds to the food banks located on or near the colder waters of the Arctic and Antarctic regions. The location of fossil remains tends to confirm the conclusions that the precursors of present day whalebone whales followed similar migration routes, and that similar types of fossilized skeletal remains occur in geological formations of corresponding age on the old shores that bordered these oceans.
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> Examination of fossilized cetacean skeletons excavated in sedimentary strata deposited on ancient beaches, estuaries and river deltas revealed that although these air breathing mammals had been adapted for habitual aquatic existence, no fundamentally new structures had been added in the course of geologic time, and that the functioning of the entire body is conditioned by adjustments of old organs to an exclusive life in the water.

The Archaeoceti, the most primitive of the three suborders of whales, dating from Eocene and early Oligocene time, are well represented in fossil collections. So also are whales from the Miocene epoch, a period of tremendous evolutionary radiation of Cetacea. Much less well known are the Oligocene ancestors of modern whale types.

While he was treating the Archaeoceti systematically, Kellogg simultaneously worked on the description of Miocene Cetacea from both coasts of North America. This study was of major concern to him from the time of his description of the humpback whale *Megaptera miocaena* from California in 1922(b), to his last paper, "Cetothere Skeletons from the Miocene Choptank Formation of Maryland and Virginia," published in 1969, the week after his death.

The difference in Kellogg's approach to the Archaeoceti and the Miocene Cetacea is significant and proper. The Archaeoceti are unified by primitive characteristics, which permit standard taxonomic treatment, whereas the variation among the Miocene forms is such that Kellogg,

rightly, usually refused to assign genera to families or to express opinions as to their relationships to modern forms. At the same time his meticulous treatment of both specimens and literature clarified many a taxonomic problem, even though it was as yet insoluble because of a paucity of data. An example is his treatment of the Squalodontidae (1923), published under the title "Description of Two Squalodonts Recently Discovered in the Calvert Cliffs, Maryland, and Notes on the Shark-Tooth Cetaceans." All genera assigned to the family are recorded and are either accepted, reassigned, or placed in limbo as insufficiently known. This last course was often preferred by him over the formal declaration of a *nomen nudum*, because the number of available specimens was so small that he felt it wise to wait for further information before making such decisions. The squalodont paper remained the definitive work on that group until Rothausen, in 1968, built upon it in his "Die systematische Stellung der europäischen Squalodontidae." Kellogg was not always taxonomically so cautious, however. In "Miocene Calvert Mysticetes Described by Cope" (1968a) he declared a number of Cope's genera, based on mandibular fragments, to be indeterminate.

Although Kellogg avoided formal taxonomic assignment to higher categories of most of the Miocene Cetacea that he described, he often discussed relationships, paleoecology, and geographic distribution. The great mass of his work on Miocene forms is indispensible for all workers on cetacean evolution: it not only furnishes them with clear and accurate information, including many evolutionary ideas, but also leaves them free of premature taxonomic assignments that would only have to be undone. This attribute of his work is particularly noticeable in his treatment of the Miocene porpoises. The Miocene produced many porpoises of modern type, undoubtedly including both forerunners and members of the modern families. At this stage of evolution, however, the distinctions between families are subtle, and it is easy to be misled by obvious characters that probably result from parallelism or convergence. While describing or analyzing a number of genera—such as *Eurhinodelphis*, *Zarhachis*, *Kentriodon*, *Phocageneus*, *Schizodelphis*, *Hadrodelphis*—he left their assignment to higher taxa for future workers. At the time of his death, he was reviewing the Miocene porpoises.

Publication of "The History of Whales" (1928a) established Kellogg as an authority in the field of cetology, and soon thereafter, in 1930, a new and important phase of his life began. In April of that year he went to Berlin as a delegate to a conference of experts on whaling matters, held under the auspices of the League of Nations. This was the first of a series of conferences on international regulation of whaling, a series that included the Washington conference of 1946, which formulated the International Convention providing for the establishment of the International Whaling Commission. In 1937, Kellogg was appointed by the State Department as United States delegate to the International Conference on Whaling at London, which resulted in the protocol of 1937, prohibiting the killing of all right and gray whales and establishing minimum legal lengths for commercial kinds of whales. The protocol of 1938 established a "sanctuary for two years for baleen whales in a sector of the Antarctic Ocean . . . and absolute protection of all whales against pelagic whaling in the North Atlantic sector of the Arctic Ocean." Kellogg was chairman of the American delegation to the conferences of 1944 and 1945 and was chairman of the Washington conference of 1946. He was United States Commissioner on the International Whaling Commission from 1949 until 1967, was vice-chairman of the commission from 1949 to 1951, and chairman from 1952 to 1954.

J.L. McHugh, Kellogg's successor as United States commissioner, has evaluated his work in the International Whaling Commission (1972, pers. comm.):

> Although the United States had long since ceased to be a major whaling nation, it continued to exert a substantial influence in world whaling matters, largely through the efforts of Remington Kellogg. He was Head of United States Delegations to the first 16 meetings of the International

Whaling Commission and attended his last meeting of that body, the 16th, at Sandefjord, Norway, in June 1964. By this time, scientific evidence of the alarming condition of the stocks of blue and humpback whales in the Antarctic was indisputable, and the Commission had already recommended, and the member nations had adopted, a complete ban on killing those species in the Southern Ocean. The scientists also had presented evidence that the fin whale resource in this region was overexploited, and that the catch quota for the Antarctic must be substantially reduced to prevent a continuation of this overharvesting. Dr. Kellogg fought very hard at the Sandefjord meeting to obtain agreement on a rational catch limit on Antarctic whaling, based on the scientific evidence. He returned from that disastrous meeting deeply discouraged by the failure of the Commission to act responsibly, and pessimistic about the future of world whale resources. It was unfortunate that illness prevented him from participating in subsequent meetings of the Commission, for the bitter controversy of the 1964 meeting, which almost destroyed the Commission, led eventually to a reversal of its do-nothing record. Since 1965, although this has not been widely recognized, a number of positive steps have been taken to place world whaling under rational scientific control. Although it has not solved all of its problems, the Commission has come a long way toward meeting its responsibilities since 1964. Remington Kellogg remained interested in the affairs of the Commission until his death, although illness prevented active participation, and his influence is still felt in many ways.

An important byproduct of the 1930 trip to Europe was the opportunity to meet European specialists and to study fossil whales in museums in Berlin, Munich, Stuttgart, Vienna, Padua, Bologna, Florence, Turin, Brussels, Haarlem, Amsterdam, and London. Whales of Miocene age have been found in sedimentary basins in Belgium, Austria, and Italy and observation of the European specimens was essential to the attempt to establish the worldwide pattern of Miocene whale distribution. Understandably, specimens described in Europe and America had almost always been given different names, yet the habits of whales today indicate the probability that Miocene genera and even species ranged widely over the oceans. Detailed comparisons with European specimens are frequent in Kellogg's papers; yet, as in his approach to taxonomy, he was conservative in suggesting trans-Atlantic relationships.

Kellogg's position in the Division of Mammals of the U.S. National Museum naturally involved him in work on groups other than marine mammals. He published an annotated list of West Virginia mammals in 1937, one of Tennessee mammals in 1939, and (with Wetmore) one of the mammals of Shenandoah National Park in 1947. He produced several studies of fossil and subfossil mammals from caves and archeological sites and in 1942 led a party in excavating Pleistocene mammals in Rampart Cave, near Boulder Dam on the Colorado River. He collaborated with his old commanding officer, E.A. Goldman, in naming 10 new white-tailed deer from North and Middle America (Goldman and Kellogg, 1940) and in a review of the spider monkeys (Kellogg and Goldman, 1944).

The advent of World War II brought new responsibilities to the Smithsonian. In 1943, as a participant in "the program for the furtherance of cultural relations with scientists of the Latin-American republics," Kellogg was one of three museum officials to visit Brazil. This three-month assignment was an experience that he remembered happily. He observed field stations and laboratories engaged in the study of tropical diseases, with particular reference to Brazilian mammals believed to be carriers of disease. In 1944 and 1945, he added to the literature of disease transmission with two papers on the macaque monkey (1944, 1945a) and with two on rodents (1945b, 1945c) in the South Pacific. In August 1947, he again visited Brazil as the delegate of the United States to the International Commission for the Establishment of the International Hylean Amazon Institute.

From the beginning of his service in the Division of Mammals, Kellogg had collaborated with Gerritt S. Miller, Jr., in the tremendous project of listing the North American Recent mammals. He carried on this work after Miller's death, and the 954-page volume was published as a bulletin of the U.S. National Museum (Miller and Kellogg, 1955).

In May 1948, Kellogg was appointed director of the U.S. National Museum, and in February 1958 he was appointed assistant secretary of the

Smithsonian Institution. He got a chuckle out of the fact that when he retired, in 1962, he was replaced by three appointees: an assistant secretary, the director of the U.S. National Museum, and the director of the National Museum of Natural History. The period of Kellogg's administrative appointments was an active one for the Smithsonian. Almost all the exhibit halls in the Natural History Museum were modernized; the scientific staff of the museum was enlarged, and many new research programs were initiated; and the new National Museum of History and Technology (now the National Museum of American History) was built. Despite the demands of these and many other activities, Kellogg managed to spend part of each day in research on fossil marine mammals.

Over the years, in addition to activities closely related to his research, Kellogg served on many bodies devoted to the advancement of science and the public interest. He was a member of the Board of Governors of the Crop Protection Institute, the Advisory Committee of the Chemical-Biological Coordination Center, the Pacific Science Board, the Board of Directors of the Canal Zone Biological Area, the Advisory Board of the Arctic Research Laboratory, the Committee on Research and Exploration of the National Geographic Society, and the Research and Development Board of the Department of Defense. He was vice-chairman of the Division of Biology and Agriculture of the National Research Council, president of the American Society of Mammalogists, and president of the Paleontological Society of Washington. He was a correspondent of the Academy of Natural Sciences of Philadelphia, trustee of the National Parks Association, fellow of the Geological Society of America, foreign fellow of the Zoological Society of London, and member of Sigma Xi, the American Academy of Arts and Sciences, and the American Philosophical Society. In 1947, he was given a citation for distinguished service by the University of Kansas. He was elected to the National Academy of Sciences in 1951.

In 1962, when he retired, Dr. Kellogg moved to an office in the Division of Vertebrate Paleontology in the newly built east wing of the National Museum of Natural History. He organized the collection of fossil marine mammals, which had perforce been neglected during his years of administration. Then he plunged into the study of the Miocene marine mammals of Maryland; as always, he brought into this work comparisons based on his wide studies. Between 1965 and 1969 he published nine major contributions to the study of fossil marine mammals. He was always hard working, but he was never too busy to discuss paleontology with his colleagues, visiting students, or children who had found a porpoise vertebra on a Chesapeake Bay holiday.

A long-time friend, Edward P. Henderson, wrote of Remington Kellogg after reading this memorial:

> The above outlines the accomplishments of this man, but neglects the unusual personality which those who were associated with him knew so well. He was recognized by all to be able in many fields, he accepted nothing as being true until it was proven, and usually he accented the negative side of all that was submitted to him, because he wanted more than one reason for accepting anything as a fact or policy. It is impossible to describe with words the expression on his face as he exploded into a few choice sentences often sprinkled with "Kelloggical" profanity and a well-known grin.
>
> His door was always open not only to the professional colleagues but to all levels of the staff, and all who came could present their case.

Dr. Kellogg's wife of nearly 50 years, Marguerite Henrich Kellogg, presented Dr. Kellogg's library on marine mammals, including the bookcases that he built for his home, to the Smithsonian Institution, where it forms the nucleus of the Remington Kellogg Library of Marine Mammalogy. His books on land mammals were presented to the University of Kansas. In his will, Dr. Kellogg expressed his intent to establish a fund for the advancement of knowledge of fossil marine mammals. Such a fund, bearing Kellogg's name, has been established by Mrs. Kellogg at the Smithsonian Institution; the National Geographic Society and friends of Dr. Kellogg have also contributed to it. A memorial fund has also

been established at the Museum of Paleontology, University of California, Berkeley, through the generosity of the late Dr. Leslie E. Wilson and Edith P. Wilson. This fund is used to support research on the Cetacea by qualified graduate students.

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# Phosphate Mining at the Lee Creek Mine

*Jack H. McLellan*

ABSTRACT

Although phosphate has been sought in North Carolina for approximately a century, prospecting leading to production began only in the 1950s and culminated in 1966 with the first shipment of concentrate from Texasgulf's Lee Creek Mine, on the south bank of the Pamlico River, near Aurora, Beaufort County, North Carolina. The mining and processing operations are described, insofar as they are relevant to the study of the geology and paleontology. The ore occurs in the Pungo River Formation, from which it is obtained by removal of 90–100 feet (27–30 m) of overburden, using dredge and dragline in an open pit mine. Access to strata in place is very limited. Most fossils are collected by prospecting the spoil piles (mostly Yorktown and overlying formations), but some are obtained from ore residue and from coarse rejects at the mill (mostly Pungo River Formation).

## Introduction

The search for phosphate deposits in North Carolina was started shortly after mining had begun in South Carolina, at the end of the Civil War. In 1883 C.W. Dabney and W.B. Phillips independently examined phosphate occurrences in Duplin County and nearby areas in North Carolina (Stuckey, 1970:15). Numerous phosphate occurrences were described in early annual reports of the North Carolina Agricultural Experimental Station, but none proved to be of commercial importance (Laney and Wood, 1909). Deposits were described from Columbus, Jones, Onslow, Duplin, Lenoir, Sampson, Bladen, and Pender counties. A few small mining operations were conducted near Castle Hayne, in Pender County.

Early in the 1950s, the American Metals Company found phosphatic sands in water well samples from Beaufort County, in the course of a search for titanium-bearing terrace deposits along the Atlantic Coastal Plain. A drilling program established the presence of extensive but deeply buried phosphorites in the northern parts of Beaufort and Hyde counties. Leases to explore the Pamlico and Pungo rivers for phosphates were obtained from the state, but these were dropped several years later.

Philip M. Brown of the United States Geological Survey revived interest in phosphate exploration when he gave a paper on ground water studies in North Carolina in 1957 (Brown, 1958). Land options were taken by several companies, and several test holes were drilled on the north side of the Pamlico River. Companies that were active at this time included Kennecott Copper Corporation, General Crude Oil Company, and several of the companies mining phosphates in Florida.

In the fall of 1959 an exploration manager of the then Texas Gulf Sulphur Company visited the area, and recommended that some studies be made on the feasibility of mining the unconsolidated sands through well holes. Several possible methods for doing this were proposed by engineers of the Frasch sulphur operations of the

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company. In the spring of 1961, Dr. Leo J. Miller of Texasgulf spent two months in Beaufort County, after which he surveyed other phosphate producing areas of the United States. He returned to North Carolina in the fall, convinced that the phosphates of Beaufort County merited additional study.

About this time Mr. A.L. Nash, Jr., of Concord, North Carolina, succeeded in flushing several hundred tons of phosphate sand to the surface from wells drilled on the north shore of Pamlico River at Gum Point. The results were not considered very promising economically, but the test did make available large samples of ore for beneficiation studies.

Dr. Miller first ran a survey of existing water wells and core holes, using a gamma ray probe. He obtained a somewhat different and more accurate picture of subsurface conditions than had been obtained by previous investigators. The uranium concentration in individual pellets of Lee Creek ore, as determined by neutron activation analysis, is in the range of 75 ppm (Spalding and Sackett, 1972). This is substantially higher than the average concentration of uranium in typical sands and clays. (For a description of the use of gamma ray logs in phosphorite exploration, see Kimrey, 1965.)

Encouraged by his preliminary results, Dr. Miller then undertook a core drilling program and blocked out a large phosphate deposit under the Pamlico river and the land to the south of the river. In June 1962 the North Carolina State Department of Conservation and Development received sealed bids for mining rights under portions of the Pamlico and Pungo rivers. Texasgulf was the successful bidder on block D, consisting of 9200 acres under the Pamlico River adjacent to the present Lee Creek Mine. The company also acquired mining rights on a large acreage of privately owned land.

Ore samples from the Nash Well at Gum Point and from some of the cores were subjected to laboratory and pilot plant beneficiation tests. The most important of these tests were run at the North Carolina State University Minerals Research Laboratory at Asheville (Redeker, 1966). It was found that the phosphate ore could be concentrated by standard flotation methods to obtain a commercial phosphate grade of 67 BPL (bone phosphate of lime), containing 30.7 percent $P_2O_5$. The concentrate compared favorably with similar material from the important central Florida (Bone Valley) field. The Beaufort County phosphate concentrate was characterized by uniform chemical composition and grain size, by a low content of iron and aluminum, and by a somewhat higher content of magnesium and organic matter than the comparable Florida product.

The geological work established the presence of a 40-foot (12-m) layer of phosphate sand overlain by 90–100 feet (27–30 m) of unconsolidated sediments in the most favorable mining area. The phosphate ore occurs in the Pungo River Formation, named by J.O. Kimrey in 1964 and more extensively described in 1965, on the basis of data from water wells and core holes, as the formation is unknown at surface. Rooney and Kerr (1967) have described the mineralogy and discussed the origin of the deposit. It was necessary to select the best method for mining and to confirm that freshly mined ore was fully amenable to the beneficiation methods that had been demonstrated on a small scale. In the spring of 1963, work was started on the design of a flotation pilot plant. In July, a large suction dredge was brought in to dig a test pit at the confluence of Lee Creek and the Pamlico River. The top of the phosphate layer was reached on 29 December 1963 and 100,000 tons of ore were pumped by the dredge into pits that had been constructed alongside the beneficiation pilot plant.

The test pit provided a valuable opportunity for inspection of the geological section. Visits were made by geologists from the state and the U.S. Geological Survey (Gibson, 1967). A geologist from the company's Frasch division was present during the entire test period to take data and report on the geological findings.

Early in 1964, sustained runs were started in the flotation pilot plant under the supervision of

Texasgulf engineers. Over five thousand tons of concentrate were produced. Both the mining and processing operations have been described in detail by Caldwell (1968) and Trauffer (1969); only a summary is relevant here. Briefly, the beneficiation process tested in the pilot plant and used in regular operations at the present time consists of removing the +14 mesh coarse material by a series of wet screening steps. These coarse rejects, about 3 percent of the dry ore, are discarded. Paleontologically, they are a rich source of small macrofossils, especially shark teeth. The −14 mesh ore slurry is then vigorously agitated (scrubbed) and subjected to a series of washing and decanting steps to remove −200 mesh silt and clay particles. This fine fraction comprises about 19 percent of the dry weight of ore. The clean 14 × 200 mesh sands consist of angular quartz grains and phosphate pellets. These are separated by two stages of froth flotation. In the first stage, the sand slurry is treated with a saponified fatty acid reagent, which causes the phosphate pellets to rise with the froth. The sand grains sink and are discharged from the bottom of the cell. This tailings sand is discharged as a waste.

The first stage flotation product is contaminated by some fine grained quartz sand, which is mechanically trapped in the froth. Therefore, the first stage product is treated with a small amount of sulphuric acid, to destroy the fatty acid reagent, and is washed. The de-oiled first stage concentrate is then sent to a second flotation step, using an amine reagent. The flotation is now inverted, with the fine quartz sand rising with the froth and the phosphate pellets sinking to the bottom outlet. The fine quartz sand is discarded. The second stage phosphate concentrate, now containing less than 2 percent residual quartz, is de-watered and conveyed to stockpiles.

The wet phosphate sand drains to a final moisture of about 11–12 percent on the large open stockpiles. Before shipping, the phosphate concentrate is heat dried to 2 percent or less moisture. This product is referred to as 67 BPL dried concentrate.

If the concentrate is heated to 1500°F in the presence of air, the organic matter contained within the pellets is destroyed. This organic material is largely fossilized bits of chitin and other animal tissue. Also, $CO_2$ is expelled from the carbonate apatite lattice. The result of this high temperature treatment or calcination is to raise the grade of the concentrate to 72 BPL, or 33 percent $P_2O_5$. Most of the Lee Creek production is as a calcined product.

An intense program of testing demonstrated that Lee Creek concentrate worked very well in all of the standard fertilizer manufacturing processes. On 2 April 1964 Texasgulf announced that it would proceed with the construction of a mine and mill in Beaufort County, to be known as the Lee Creek Mine. By June, design work was underway for a mill to produce three million tons per year of concentrate. On 1 April 1966, two years after the announcement, the first car of phosphate concentrate was loaded and shipped from Lee Creek.

Today, the phosphate operations of Texasgulf Chemicals Company, a Division of Texasgulf Inc., is a complete phosphate mining and fertilizer manufacturing complex (Figure 1), representing an investment of over 400 million dollars. Sulphur shipped from Texas and other places is converted into sulphuric acid in five large units, with a combined capacity of three million tons of sulphuric acid per year. All of this acid is consumed in the Lee Creek fertilizer plants. It is reacted with calcined phosphate concentrate to make dilute phosphoric acid. The weak acid is concentrated and shipped to liquid fertilizer plants in many parts of the country. Some of the phosphoric acid is consumed at Lee Creek to make solid fertilizers, such as triple superphosphate and diammonium phosphate. Bulk products are shipped by rail and by barge. Some of the production enters the export market via the port at Morehead City, North Carolina.

### The Lee Creek Mine

The open pit mine of the Phosphate Operations is located north of Aurora, Beaufort County,

FIGURE 1.—Lee Creek Mine, 1972, oblique aerial view looking southwest from above Pamlico River, showing entire phosphate operation at that time, now expanded. Courtesy of Texasgulf Inc.

North Carolina. The mine and associated plants are on the south bank of the Pamlico River in Richland Township. Lee Creek was a small local drainage feature, which was closed as the mine was expanded through the area.

The 40-foot (12-m) thick phosphatic sand layer, in the Pungo River Formation, is covered by 90–100 feet (27–30 m) of sands, clays, shell beds, and thin limestone layers. The ground surface is about 10 feet (3 m) above mean sea level. The area was covered by second growth pine forest at the time that development of the mine started.

At the beginning, various methods for mining were reviewed by Texasgulf, as well as by other companies with land holdings in the area. Texasgulf started in business many years ago on the Gulf Coast by using the Frasch process to recover sulphur through drill holes. Attention was given to well recovery methods for mining the phosphate sands and some wells were drilled and tested. The experiments were not very successful, and the method was abandoned.

Finally a decision was reached to dig a test pit. In 1963, a 20-inch (50.8-cm) suction dredge with

a rotary cutter and a pumping capacity of 14,000 gallons per minute was brought in on the Pamlico River. The dredge cut a channel into Lee Creek and then excavated a basin approximately 900 feet (274 m) in diameter on the east bank of the creek, on the Butt tract. A spoil area was set up along the south bank of the Pamlico River. After digging to the maximum depth of the cutter arm, a dam was built to seal off the test pit. The pool level was lowered in successive stages of about 20 feet (6 m) each until the top of the ore was reached. With each lowering, the pit diameter was decreased, forming a series of benches. Detailed studies of ground-water flow were carried out while the test pit was being dug.

The test pit demonstrated that with proper benching no problems would be encountered with slumping and caving of the walls. It was found that at low drawdown levels the upward water seepage from the underlying Castle Hayne aquifer was excessive. Texasgulf engineers and geologists concluded that the best method of mining would be to depress the natural water level of the aquifer locally and to operate a dry open pit mine. This method insured minimum dispersal of the overburden and allowed orderly restoration of the land after removal of the ore.

Studies made by Texasgulf geologists and by a number of consulting ground water experts convinced the company that depressurizing the extensive Castle Hayne aquifer at the mining site would in no way jeopardize this valuable water resource (Hird, 1970). It was recognized that many shallow wells in the area would be affected by a lowering of the piezometric surface, and the company stood ready to replace all such affected wells by deeper ones of equal capacity. A cooperative effort by Texasgulf, other mining companies, state and federal agencies and leading experts in hydrology was made over a period of five years to understand the behavior of the aquifer, and to assess the effects of mining on the water supply, both now and in the distant future. It was formally concluded that no long range problems would result from an open pit mining operation.

In present practice, 13 wells are located in a pattern on three sides of the open pit mine. Each well has a capacity of 3000 GPM (gallons per minute), giving a combined flow of about 40,000 GPM. The water is collected in ditches and most of it is used as cooling water in the adjacent fertilizer plants. Part of the water leaving the coolers is returned to the mine for slurrying the ore. The slurry is then pumped to the mill for processing. The balance of the cooler effluent water goes to the mill and is used in washing the sands being processed by froth flotation. Thus, all of the water withdrawn from the ground to maintain a dry pit is used for essential operations in the mill and processing plants. These uses do not impair the water quality.

In the early years, mining at Lee Creek was done entirely with large electric draglines (Figure 2). The first machine was a Bucyrus-Erie 2550-W walking dragline, weighing nearly 4400 tons. The 72-cubic-yard (55-$m^3$) bucket holds 100 tons of earth, which it can swing in a circle 580 feet (177 m) in diameter, at the end of a boom 300 feet (91.4 m) in length. The electric motors total 10,000 HP and are fed by trailing cables from a mine substation. The dragline is supported on a base or tub 72 feet (22 m) in diameter, and uses lateral walking shoes to propel itself at approximately one-sixth mile (268 m) per hour. In 1973, a second large dragline, a Marion 8550 machine with a 50-cubic-yard (38-$m^3$) bucket, was purchased. There are also several smaller draglines ranging downward in size from 19-cubic-yard (14.5-$m^3$) buckets.

In open pit mining by dragline, overburden is cast aside to expose the ore (Figure 3). The overburden is stacked in a long pile or windrow, in a previously mined cut. In the method originally used at Lee Creek the dragline operates from an intermediate bench which is 30–40 feet (9–12 m) below ground level. The dragline proceeds through repeated series of three operations: (1) Cutting the working bench and stacking this material in the previously mined cut. A dragline is not very efficient in this "chopdown cut," working with material at the same level as the

FIGURE 2.—Dragline on working bench after chopdown, lifting 72-cubic-yard (55-$m^3$) bucket containing 100 tons of phosphate ore (dark colored) to be stacked in background at surface for slurrying and piping to mill. Spoil windrow in foreground. Courtesy of Texasgulf Inc.

machine. (2) Cutting the overburden which is below the bench. This material, consisting mainly of Yorktown Formation and uppermost Pungo River Formation, including the thin limestone layers, is stacked on top of the spoil pile formed by the chopdown cut. Most of the vertebrate, and many of the other, fossils are recovered by prospecting these spoil piles, and most are derived from the lower beds of the Yorktown Formation because those beds blanket the windrows and are richly fossiliferous. (3) Cutting the exposed block of ore. This ore, derived entirely from the Pungo River Formation, with as little contamination from above as possible, is placed in piles at ground level. In this and the preceding operation the dragline excavates material that is below the machine, and at this work it is very efficient.

Although it is not readily apparent, the mining operation involves some very precise geometrical relationships. The dragline must be positioned so that it can reach both the crest of the spoil pile it is building and the ore pile being formed at ground level. The spoil pile cannot be too close, or the foot of the pile will rest against and contaminate the exposed layer of ore.

This type of mining offers complex problems in soil mechanics. The working bench must be stable in order to support the heavy ground loads imposed by the dragline. The long wall must not cave or slump, or the machine will be endangered and the ore will be contaminated. It is extremely important that the windrow or spoil pile have a steep slope, otherwise the spoil will slump against the exposed layer of ore, leading to poor mine

FIGURE 3.—Oblique aerial view of mine area, 1972, looking southward. At this writing, mining has reached Durham Creek, turned southward, and now eastward, and the spoil area shown here, a rich source of fossils, has been reclaimed. Courtesy of Texasgulf Inc.

recovery. The mine engineers had to develop a knowledge of the handling and stacking characteristics of each lithological unit in the section. Moisture content is critical in maintaining steep slopes, and methods for controlling surface and ground-water flows had to be devised.

The original mining block was advanced westward at a rate of about 75 acres per year. The mine advance was on a straight wall about 3500 feet (1067 m) long (Figure 3). When Durham Creek was reached, the advance was turned southward and then eastward. Each cut was 150 feet (45.7 m) wide. The dragline started at one end of a cut, and when that was completed the machine walked back to the beginning end and started a new cut.

Because of the large scale of the operation, the depth of the cut, ever-present water, and the danger of slumping, direct access to strata in place in the mine wall for paleontological prospecting and stratigraphic study has been extremely limited, except for strata above the working bench.

As mining rates increased and land restoration work intensified, improvements in handling the upper overburden layers were needed. Marshy

ground provides poor support for heavy equipment. In 1974, a 27-inch (69-cm) dredge was purchased, and in 1980, a 30-inch (76.2-cm) dredge was acquired. These dredges are used to develop mining blocks several years before the draglines move in. After trees are cut and vegetation is removed in a new area, a dredge enters and cuts a pond about 80 acres in area. The dredge excavates to a depth of 30 to 40 feet (9 to 12 m) corresponding to the removal of the chop-down material. The dredge then starts a new pond, and the finished tract is drained by pumping. After thorough drying, the block is ready for mining by draglines. The bottom of the pond becomes the working level or bench for the dragline.

Using dredges to remove the surface and upper layers offers several advantages: (1) A floating dredge can cut its own channels and pond and is ideally suited for work in marshy lands. (2) A dredge can move the material it excavates long distances. Dredge spoil is moved by pumping through pipelines for distances up to 2 miles (3.2 km) at Lee Creek. This greatly facilitates restoring and leveling mined-out areas. (3) The digging efficiency of the dragline is improved. By working on a dry and stable bench and having to deal only with material below the bench level the machine can work at maximum capacity. (4) Ore recovery is better. The spoil piles are not as high, since less overburden has to be stacked immediately adjacent to the exposed ore layers. The spoil piles are more stable. All of the ore can be removed without contamination by slumping spoil piles.

The combination of a dredge to remove the upper overburden and an electric dragline to remove the lower overburden and recover the ore is a very satisfactory method for mining the Lee Creek phosphatic sands. This development has significantly increased Texasgulf's capacity to produce phosphate ore. However, introduction of the dredge has not been conducive to field study of strata above the working bench. Thus far the lower spoil piles seem to be less productive paleontologically, but experience under the new conditions is as yet very limited.

The land reclamation program is proceeding now at full rate. In a well-controlled operation, the same amount of land is reclaimed each year as is newly mined each year. After several years of standing and compacting of the spoil piles, additional material is pumped by dredge to level off the surface. It is during this interval prior to reclamation that paleontological prospecting of the spoil piles is carried out. After a short drainage period, the land is ready for re-use. Experimental plantings have demonstrated that the restored land will support a vigorous growth. Studies are in progress on the optimum mixtures of clay and silt washed from the ore, waste gypsum from the phosphoric acid plant, and sand tailings to produce a good cover soil. Gypsum is a particularly valuable soil amendment. Large tonnages are shipped from Lee Creek for use on peanut fields in Virginia and North Carolina. Phosphogypsum contains valuable amounts of the primary plant nutrient, $P_2O_5$, and is very rich in the secondary nutrients, calcium and sulphur.

On an average day the mill requires more than 40,000 tons of ore (dry basis). The ore is transported to the mill as a water slurry containing about 35 percent solids. Hydraulic monitors are used to wash the piles of ore into a pit in the ground. Large portable pumps with 1000 HP motors suck the slurry from the pit and pump it through 2 miles (3.2 km) of 18-inch (46-cm)-diameter piping to the mill. The slurry of clay, silt, sand, and water carries rocks up to 5 inches (12.7 cm) in diameter through the line. About 12,000 gallons per minute of water are used to transport 17 tons per minute of ore in each pipeline to the mill. Booster pumps are used at intermediate points in the line.

The ore is predominantly loose sand. Some rubble, such as large fossils and broken pieces of indurated layers, is left behind at the ore pumping stations, and this is periodically cast aside by a small dragline. This ore residue has been a source of some important fossils from the Pungo River Formation. The pumping stations are temporary installations and the equipment has to be dismantled and moved every week or so as the big dragline progresses along its cut on the mine face.

In 1982, Texasgulf was the only company mining phosphates in North Carolina. Several other companies have extensive land holdings in the area. North Carolina Phosphate Corporation has done some site work and has had some mining equipment delivered, but it has announced no plans to start a mine. NL Industries Inc. and FMC Corporation are reported to have done some exploration and test work on the phosphate deposits.

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# Stratigraphy of Miocene through Lower Pleistocene Strata of the United States Central Atlantic Coastal Plain

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## ABSTRACT

Miocene, Pliocene, and Pleistocene strata were deposited in two embayments in the central Atlantic Coastal Plain, the Salisbury to the north and Albermarle to the south. Both embayments underwent local tectonics, and no single area within either has a continuous section.

Deposition in both embayments began in early Miocene time. In the Salisbury embayment, the early deposits were largely biogenic (Fairhaven Member of the Calvert Formation), and the center of deposition was located in Maryland. Relatively continuous clastic deposition commenced in the late early Miocene and continued through the middle Miocene (Plum Point Marl Member of the Calvert Formation and the Choptank and St. Marys formations). Deltaic deposition began in the northern part of the embayment, as seen in the Calvert and Kirkwood formations and influenced environments west of the delta lobe. The center of deposition in the Salisbury embayment shifted southward into Virginia during late Miocene time ("Virginia St. Marys" beds) and continued there through the early and middle(?) Pliocene (Yorktown Formation); only the southeastern part of the embayment received sediments in the late Pliocene and early Pleistocene (uppermost part of the "Yorktown" Formation). Environments throughout this time were largely inner shelf (less than 60-m depths), and some marginal-marine to nonmarine intervals.

The Albemarle embayment in North Carolina received largely biogenic and biochemical deposition during the early and early middle Miocene (Pungo River Formation). This was followed by uplift in the late middle and late Miocene. Clastic sedimentation started near the Miocene-Pliocene boundary and continued with minor hiatuses throughout much of the Pliocene and into early Pleistocene (Yorktown, uppermost part of the "Yorktown," Duplin, Croatan, and Waccamaw formations). Some Pungo River strata formed in middle-shelf environments as deep as 100 m; most younger strata were deposited in inner-shelf environments (less than 60-m depth), but some in marginal-marine intervals.


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## Introduction

The Lee Creek Mine in eastern North Carolina exposes Miocene, Pliocene, and Pleistocene strata, which in most of this area are otherwise available only in subsurface borings. This paper presents the general geologic setting of the strata in the mine and related strata from southern New Jersey to southern North Carolina and provides an interpretation of depositional environments. These strata represent extensive Cenozoic transgressions. They rest upon strata ranging in age from Cretaceous to late Oligocene in various parts of New Jersey, Maryland, Virginia, and North Carolina. In some areas, the strata transgress sufficiently westward to rest upon Piedmont crystalline rocks.

The central Atlantic Coastal Plain contains two adjacent major embayments, the Salisbury and Albemarle, in which structural activity and

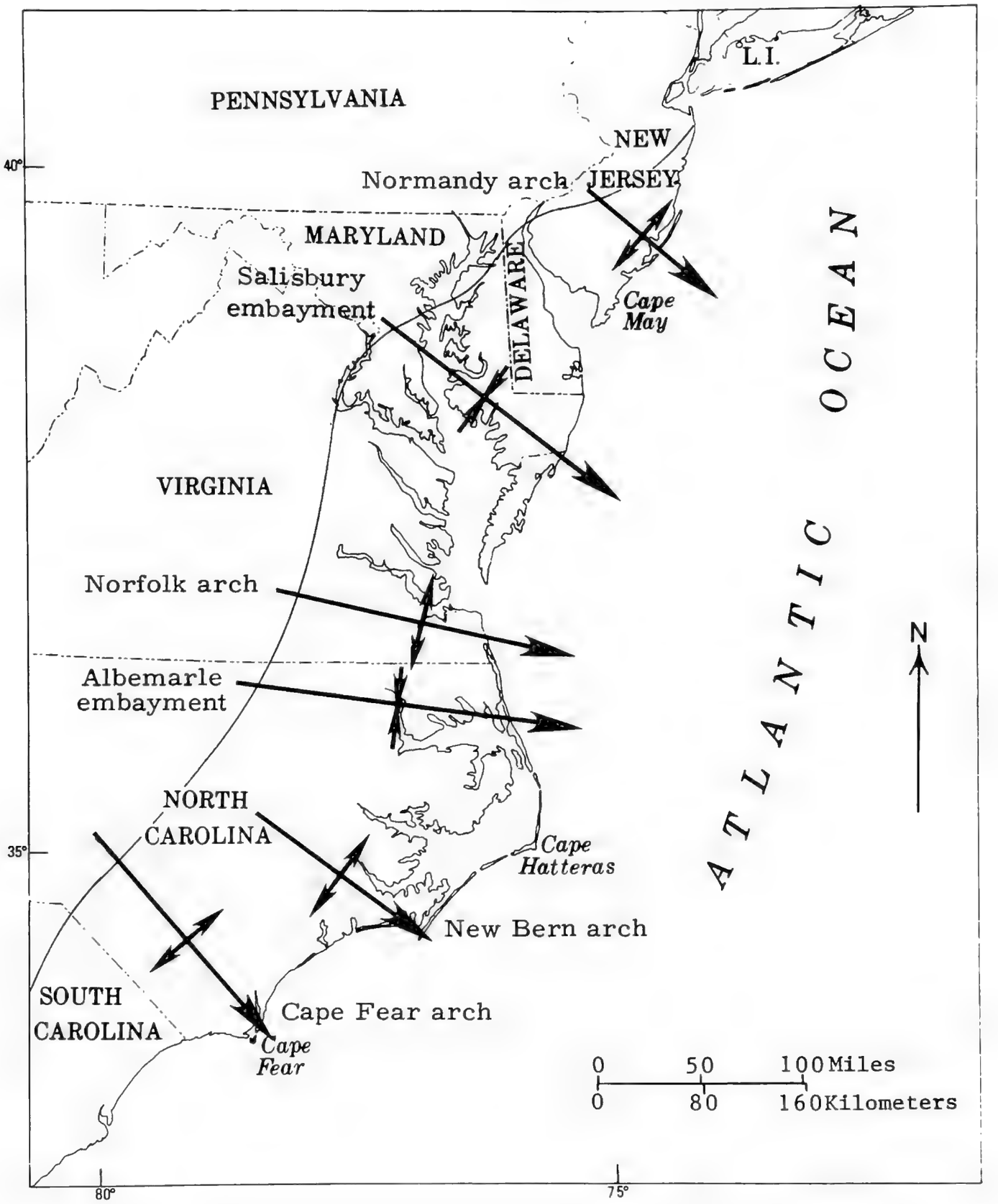


FIGURE 1.—Map showing major embayments and arches of the middle Atlantic Coastal Plain during the Miocene and Pliocene (from Gibson, 1967; Brown, Miller, and Swain, 1972). Line shows present westward limit of Miocene, Pliocene, and lower Pleistocene strata.

sedimentary patterns sometimes coincided. The embayments are separated by the Norfolk arch (Figure 1), which affected sedimentary patterns and thicknesses during Miocene and Pliocene time. The embayments are shoreward extensions of the Baltimore Canyon Trough (Poag, 1978:262).

Part of the lithologic data is from surface outcrops; these are correlated by use of mollusks (particularly the pectens), ostracodes, and foraminifers. The rest is from subsurface cuttings and cores that are correlated by foraminifers, lithologic character, and stratigraphic position. The basis for the age assignments of the formations is discussed on pages 356–367. Figure 2 is a correlation chart of the late Oligocene through early Pleistocene strata in this area.

The paleoenvironments are reconstructed from lithologies (both individual localities and regional patterns) and faunal data. The faunal interpretations are based largely upon modern benthic foraminiferal ecology (upon the known environmental tolerances of individual species and groups of species); in Miocene strata, where species that have living representatives are less numerous, assemblage characteristics (e.g., species diversity and abundance of planktonic specimens) were used. (See Phleger, 1960; Walton, 1964; Gibson, 1968; Gibson and Buzas, 1973; J.W. Murray, 1973, and Boltovskoy and Wright, 1976, for discussions and further references.) Some environmental interpretations are made from the molluscan assemblages following Gernant (1970) and Bailey (1973).

The lithologic and paleoenvironmental patterns that are evident onshore, in conjunction with the biostratigraphic data presented by Gibson (pp. 368–402), will permit more detailed correlations of equivalent strata found in offshore borings (Poag, 1978).

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## Previous Work

Comprehensive works on the Miocene and Pliocene strata of Maryland (Clark, Shattuck, and Dall, 1904), Virginia (Clark and Miller, 1912), and North Carolina (Clark et al., 1912) were published within a short time span in the early part of the 20th century. Later references include Mansfield (1943), Richards (1945), Spangler (1950), Spangler and Peterson (1950), G.E. Murray (1961), Maher (1965, 1971), Gernant (1970), Glaser (1971), Brown, Miller, and Swain (1972), Teifke (1973), and Weaver and Beck (1977).

The structural framework affecting the distribution of Coastal Plain strata generally has been considered to be controlled by warping in the basement rocks. These warps influenced the locations of the sedimentary basins as indicated by Stephenson (1928) and Mansfield (1929, 1937). Cederstrom (1945) and Ferenczi (1959) concluded that some of the positive and negative structures are fault controlled, thus accounting for the rapid lateral changes in thickness in some units. Subsurface control, however, is sparse along the possible fault zones, and the fault traces have not been detected in the exposed strata. Brown et al. (1977) presented evidence of a wrench fault in North Carolina, but no direct evidence of fault planes in the Miocene and Pliocene strata yet has been published. In the present investigation, the positive geologic structures are called arches, without distinguishing the mechanism by which they were formed. Figure 1 shows the location of

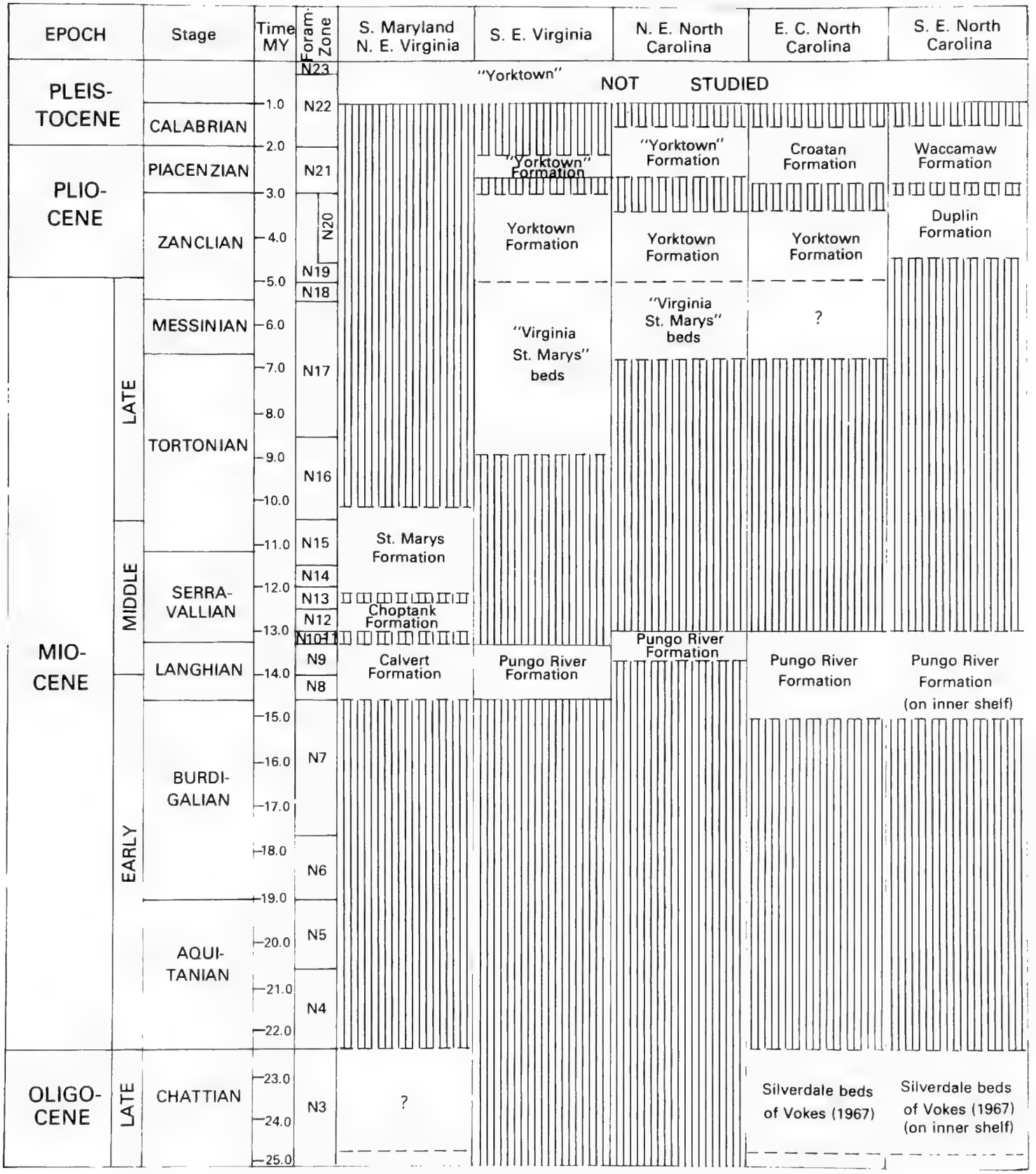


FIGURE 2.—Correlation chart for strata of late Oligocene through early Pleistocene age in the central Atlantic Coastal Plain. Stages, time scale, and planktonic foraminiferal zones are from Berggren and Van Couvering (1974). Solid lines at formational boundaries indicate well-documented time limits; dashed lines indicate limits that are incompletely known.

proposed structures in the Coastal Plain taken from Gibson (1967) and Brown, Miller, and Swain (1972).

The complex positive or negative movements of one of these structures is seen in the New Bern area of North Carolina. The Miocene and Pliocene formations are strongly influenced by a positive feature, the New Bern arch (Figure 1). For example, the Pungo River Formation is composed of strata that were deposited in middle-shelf environments in much of the Albemarle embayment (Gibson, 1967); the formation thins southward from the Lee Creek Mine toward the New Bern arch and the strata are of shallower water origin. At New Bern, on top of the feature, the formation is entirely absent (Figure 3). Similar southward thinning of strata and appearance of shallower water facies toward the arch is shown in the Yorktown Formation (Gibson, 1970). An opposing distributional pattern is seen in the uppermost Oligocene strata, such as those found at Silverdale, Pollocksville, Belgrade, along the Trent River, and in the New Bern quarry of Superior Stone Company. Although these Oligocene strata are well represented over the New Bern arch, indicating a depositional low, they are absent throughout most of the Albemarle embayment to the north. This change in environment in the Albemarle embayment, from a largely nondepositional or erosional area in the late Oligocene to probably the most persistent and deepest basin in the Miocene and Pliocene, suggests that features such as the New Bern arch may be fault controlled rather than a simple upwarp.

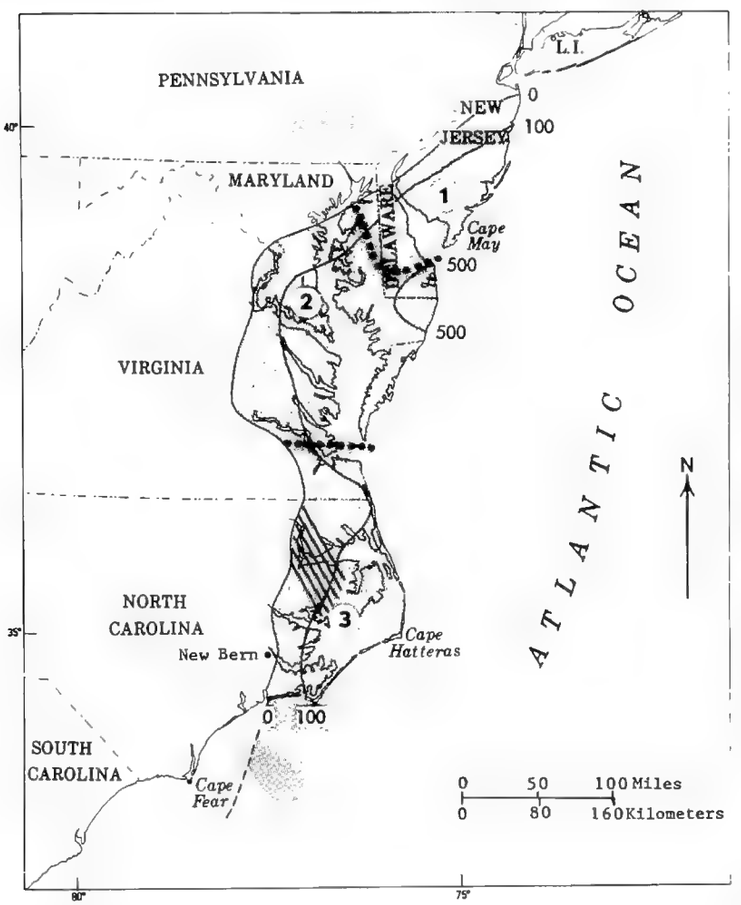


FIGURE 3.—Isopachous map of upper lower and lower middle Miocene strata. 1 = Kirkwood Formation, 2 = Calvert Formation, 3 = Pungo River Formation; contours are in feet, the dotted lines show the approximate location of the facies changes between the formations; the diagonal-lined area in North Carolina is the known location of the youngest, planktonic zone N11 strata of the Pungo River Formation (modified from Gibson, 1970).

Another anomalous distribution of strata, which apparently resulted from structural movement, is seen in the Paleocene and Eocene strata of Maryland and Virginia. Shifflett (1948) described the relatively thick sections of Aquia Formation (lower and upper Paleocene) and Nanjemoy Formation (lower and middle Eocene) in Maryland west of Chesapeake Bay and pointed out that strata of these ages are largely or completely absent on the Eastern Shore of Maryland, even though the Eastern Shore commonly was considered a down-dip area where one could expect thicker sections. A similar pattern is found in Virginia where the Aquia and Nanjemoy formations are found in most of the central and inner Coastal Plain, but are absent to the east in the subsurface of Norfolk (Brown, Miller, and Swain, 1972:46–47).

To understand the complex structural and stratigraphic patterns, Brown, Miller, and Swain (1972) examined Mesozoic and Cenozoic strata in more than 2200 wells from Long Island to South Carolina. They described the structural architecture of the Atlantic Coastal Plain as being dominated by lateral and vertical movements along a system of intersecting hinge zones. The stratigraphic intervals used by them in the Miocene included rocks of middle Miocene age (equals the Calvert, Choptank, and St. Marys

formations) and a unit of rocks of late Miocene age (equals the St. Marys Formation of Virginia of Mansfield (1943) and the Yorktown Formation, units subsequently considered to be of late Miocene and Pliocene age). They presented a combined isopach, lithofacies, and permeability distribution map for each of these units. Some of the units, such as the rocks of middle Miocene age, were considered to have depositional alignments and thickening trends accordant with the present-day configuration of the underlying basement surface. Other units, the upper Miocene, for example, were considered to have depositional alignments and thickening trends independent of the present-day basement configuration.

## Stratigraphy

The Miocene, Pliocene, and lower Pleistocene formations are discussed from oldest to youngest in the following sections. For each formation, the lithology and thickness in the type area are described, followed by a discussion of the areal distribution and paleoenvironments. Facies changes and times of deposition are emphasized, especially to contrast the Salisbury and Albemarle embayments. The locations of important outcrop and well sections specifically mentioned here are shown in Figure 4.

### Calvert Formation

The Calvert Formation was named by Shattuck (1902) from well-developed exposures in the Calvert Cliffs along the western shore of Chesapeake Bay in Calvert County, Maryland (Figure 4: loc. 16). An outcrop thickness of 150 to 170 feet (46 to 52 m) for the formation was determined by the superposition of discontinuous sections (Shattuck, 1904, pl. 5). This thickness in the type area is supported by a continuous core hole drilled in 1968 at the Calvert Cliffs site of the Baltimore Gas and Electric Company's (BG&E) nuclear power plant near St. Leonards, Maryland (Figure 4: loc. 15). At this location, slightly down-dip from the type outcrops, the Calvert Formation is 200 feet (61 m) thick (Figure 5). The thickest known section onshore is in the Hammond Well on the Eastern Shore of Maryland (Figure 6), where 500 feet (152 m) of section was assigned to the Calvert by Anderson (1948:18).

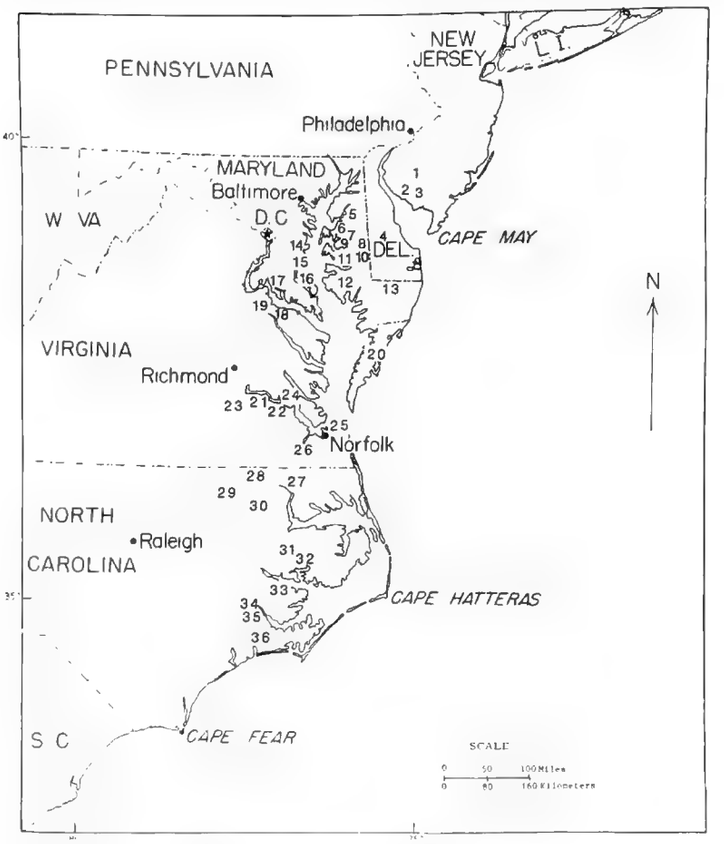


Figure 4.—Localities of outcrops and well sections mentioned in text: 1 = Well NJ2, 2 = Well NJ3 and Shiloh, 3 = Well NJ1, 4 = Greenwood Well, 5 = Well 231, 6 = Well 229, 7 = Well 228, 8 = Well 225, 9 = Well 227, 10 = Well 224, 11 = Well 226, 12 = Well 220, 13 = Hammond Well, 14 = Fairhaven, 15 = BG&E Well, 16 = Calvert Cliffs, 17 = Popes Creek, 18 = Nomini Cliffs, 19 = Oak Grove core hole, 20 = Accomack Well, 21 = Well 217, 22 = Claremont, 23 = Petersburg and Lieutenant Run, 24 = Jamestown, 25 = Moores Bridge Well, 26 = Well 209, 27 = Gatesville, 28 = Murfreesboro, 29 = Halifax, 30 = Palmyra, 31 = Terra Ceia, 32 = Belhaven, 33 = Lee Creek Mine and AU-1-GRL core hole, 34 = New Bern, 35 = James City, 36 = Great Lake Well 181.

Two relatively distinctive lithologies were recognized in the Calvert Formation in Maryland by Shattuck (1904) and given member status. The lower, Fairhaven Diatomaceous Earth Member, contained basal pebbly sands overlain by highly diatomaceous clay to fine sand intervals. This member is largely olive-gray to olive-green,

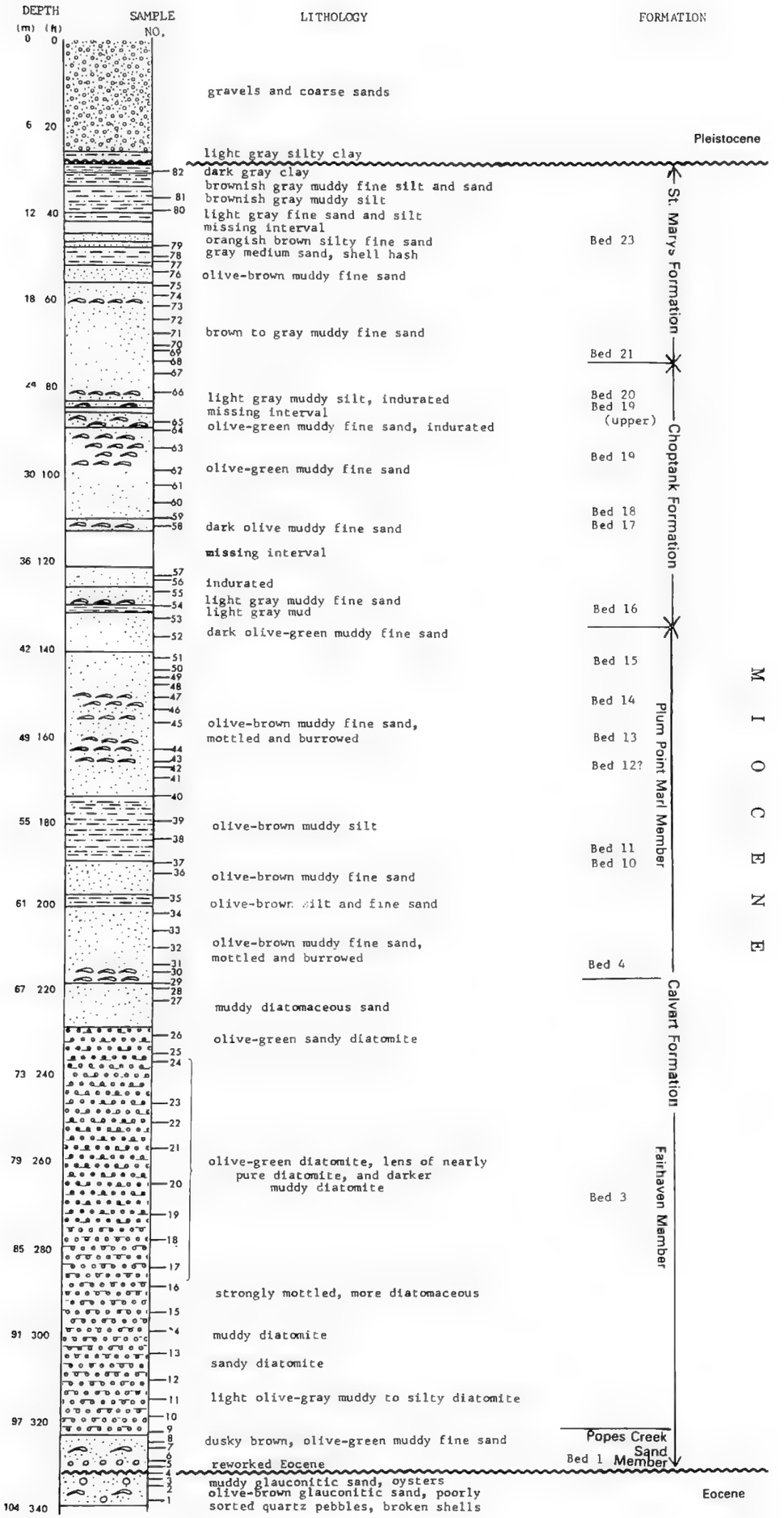


FIGURE 5.—Geologic column for Baltimore Gas and Electric Company Well (BG&E) at nuclear power plant site at Calvert Cliffs, southeast of St. Leonards, Calvert County, Maryland.

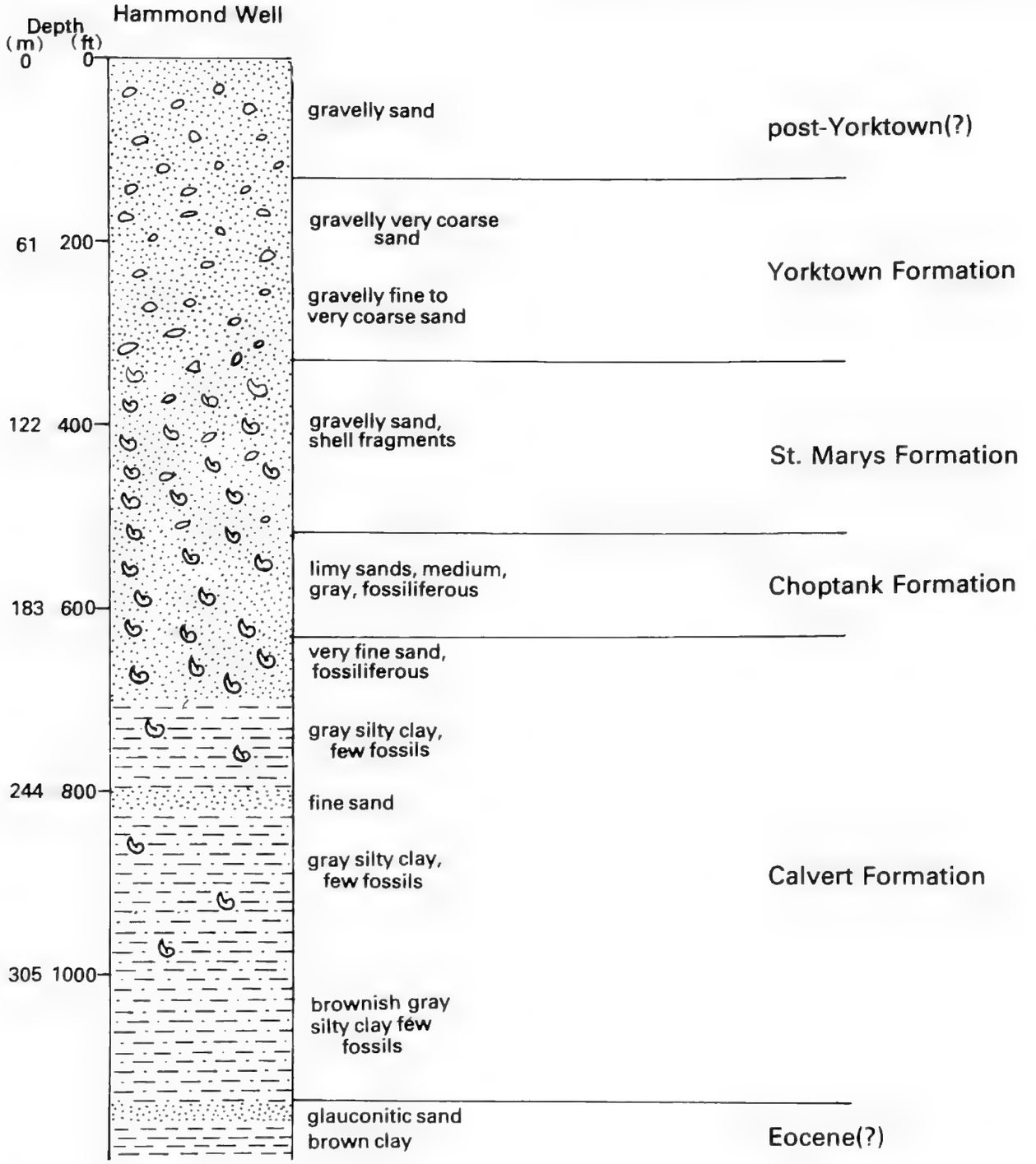


FIGURE 6.—Geologic column for Larry G. Hammond Well, Dorchester County, Maryland, showing inner-shelf facies in Calvert and Choptank formations and delta front to topset delta conditions in St. Marys and Yorktown formations.

and varies from relatively pure diatomite (as much as 65 percent of the sediment (Glaser, 1971:41)) to sandy and muddy diatomite (Figure 5). The member is 60 to 70 feet (18 to 21 m) thick in outcrop (Shattuck, 1904, pl. 5) and thickens down-dip to about 100 feet (30 m) in the BG&E Well (Figure 5). West of Chesapeake Bay, the top of the Fairhaven is marked by a distinct discontinuity indicated by an undulating surface that is overlain by a thin oyster bed of the Plum Point Marl Member (Dryden, 1936). Calcareous fossils are scarce in the diatomaceous beds in outcrop

(Gibson et al., 1980), but Foraminifera are present in the uppermost, more sandy and less diatomaceous part, and Mollusca are found in the basal sand. Foraminifera are found throughout the diatomite beds in the BG&E core, although they are lacking in the diatomaceous intervals in many other subsurface sections.

The lower beds of quartz sand in the Fairhaven Member are characterized by olive-brown, olive-green, to light greenish white fine to medium sand, muddy in places, that may contain coarse sand to fine gravel pebbles of quartz, phosphate, and glauconite. A thin layer of quartz and phosphate pebbles, bone fragments, and phosphatized mollusk shells is often found at the base. Cylindrical burrows are common in the sands. These sands crop out in Maryland west of Chesapeake Bay from near Fairhaven southward to Popes Creek, a tributary of the Potomac River, and extend into Virginia where they are muddier and thinner, such as those in the Oak Grove core (Reinhardt, Newell, and Mixon, 1980). The equivalents of zones 1 and 2 can be traced in the subsurface of the Eastern Shore of Maryland, where basal sands containing *Pecten humphreysii* are found in Well 220 (Figures 4: loc. 12; and 7), and into Delaware, where Valia, Khalifa, and Cameron (1977) described the basal unit as pebbly glauconitic and quartzitic sands containing typical Calvert Foraminifera. Poag (1978) reported conspicuous glauconite in the lower few meters of the probable Calvert Formation equivalent in core holes in the Norfolk Canyon area east of the Delmarva Peninsula, extending the distribution even beyond the edge of the present-day shelf. Because of the wide distribution of these distinctive sands (which represent the basal transgressive unit of the rapidly subsiding Salisbury embayment) and because of their lithologic distinction from the remainder of the Fairhaven Member, I herein classify them as the Popes Creek Sand Member of the Calvert Formation (Figure 9). The type section is the outcrop 100 yards (91 m) southeast of the mouth of Popes Creek, Charles County, Maryland, on the north bank of the Potomac River (Figure 8). Glauconite is rare (Glaser, 1971:46) in the western outcrop exposures, but increases to significant proportions eastward. Valia, Khalifa, and Cameron (1977) showed that beds, which I consider a part of this member, consist of 20 to 50 feet (6 to 15 m) of pebbly glauconitic sand in the subsurface of Delaware.

The thickest part of the outcropping Fairhaven (zone 3 of Shattuck, 1904) is retained as the Fairhaven Member. This member comprises the sandy and muddy diatomaceous strata above the Popes Creek Sand Member and below the shelly sand of the Plum Point Marl Member.

The Plum Point Marl Member consists of beds of olive-green to olive-brown silty and clayey fine sand that generally contain scattered to highly abundant molluscan shells, a considerable number of marine mammal bones, and other vertebrate remains. Zones 4 to 15 of Shattuck (1904) compose this member, which reaches a thickness of 90 to 100 feet (27 to 30 m) in outcrop along the Calvert Cliffs.

Areal Relationships.—Very little change is found in the Calvert Formation from the Calvert Cliffs area (Figure 5) eastward to Well 220 near Bucktown (Figures 4: loc. 12; and 7) on the Eastern Shore of Maryland. Well 220 is 20 miles (32 km) obliquely down-dip from the BG&E Well, and the similar thickness and lithology is somewhat surprising. The Calvert in Well 220 is only slightly thicker than at the outcrop (~220 ft, 67 m), and the facies are similar to those in the BG&E core. The Popes Creek Sand Member is slightly thicker in Well 220 (25 ft, 7.6 m) and is more glauconitic in the lower part. The Fairhaven Member is almost identical in the two wells as Well 220 has 110 feet (34 m) of green diatomaceous clay. The Plum Point Marl Member also is similar; Well 220 has 85 feet (26 m) of sand and sandy clays generally containing scattered shells, but abundant shells in some places.

About 30 miles (48 km) to the east of Well 220, the Ohio Oil Company's Larry G. Hammond Well (Figure 4: loc. 13) penetrated 500 feet (152 m) of Calvert (Anderson, 1948). Here the entire Calvert consists of brownish gray to gray silty

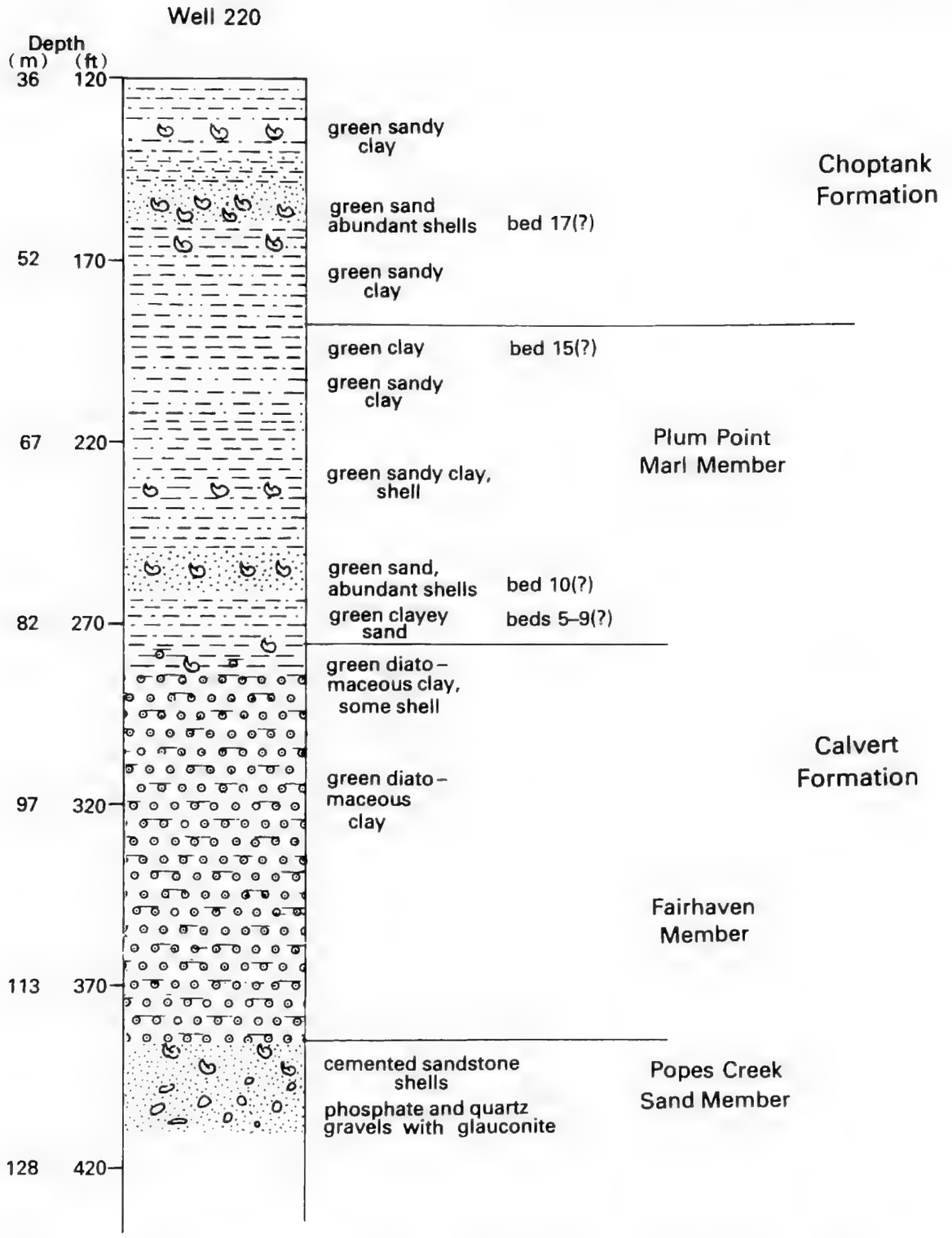


FIGURE 7.—Geologic column for Well 220, near Bucktown, Dorchester County, Maryland, showing inner-shelf facies of Calvert and Choptank formations with well-developed basal member of Calvert.

clay and very fine sand containing mollusk shells and rare to moderate amounts of glauconite scattered throughout (Figure 6). The three members of the Calvert, so characteristic to the west, are no longer recognizable. These changes in the Calvert Formation are shown in Figures 5–7.

Lithologies similar to those of the lower and upper parts of the Calvert in the type area are

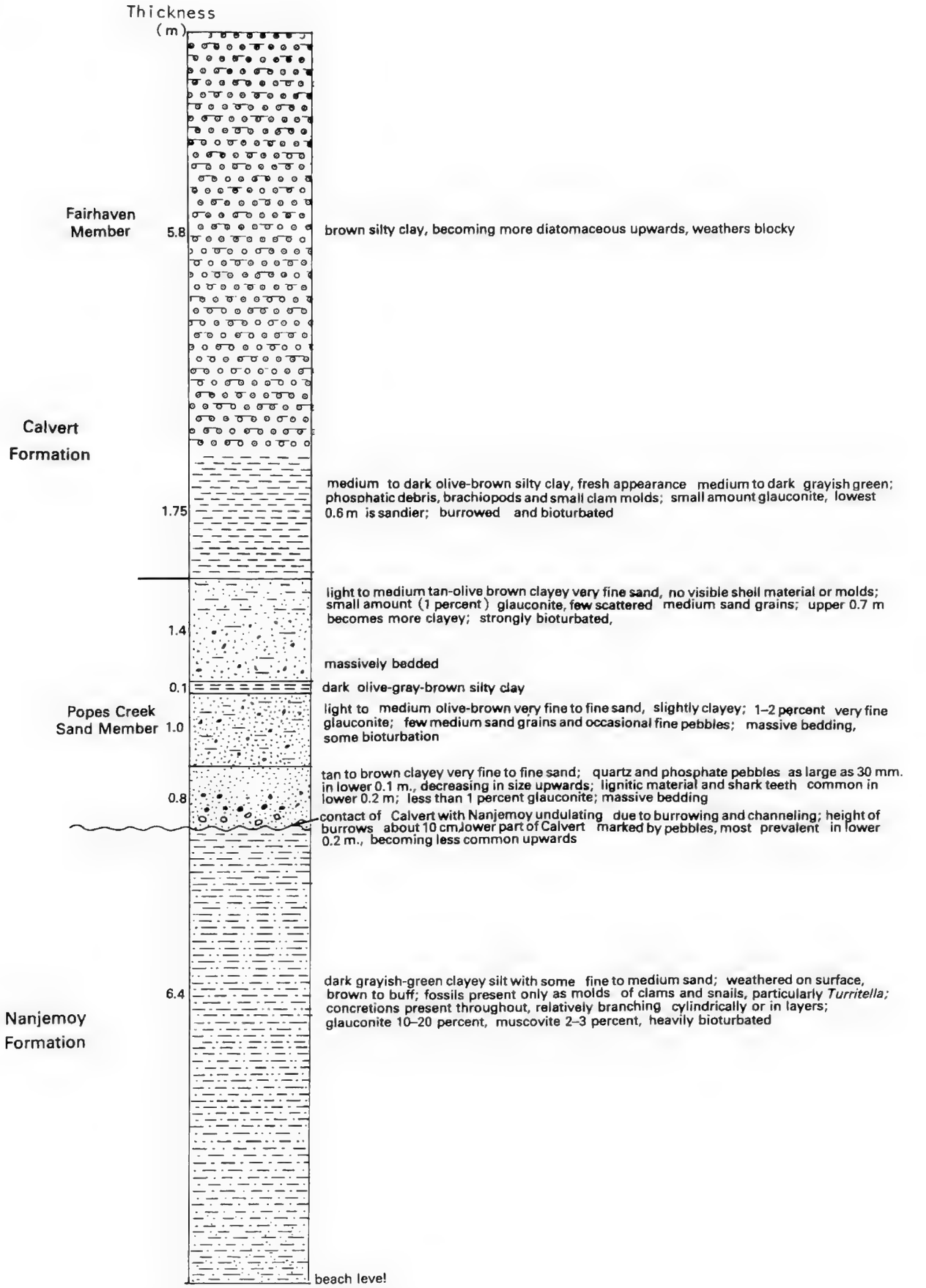


FIGURE 8.—Geologic section on north bank of Potomac River, 100 yards (91 m) southeast of the mouth of Popes Creek, Charles County, Maryland. This outcrop is the type section of the Popes Creek Sand Member of the Calvert Formation.

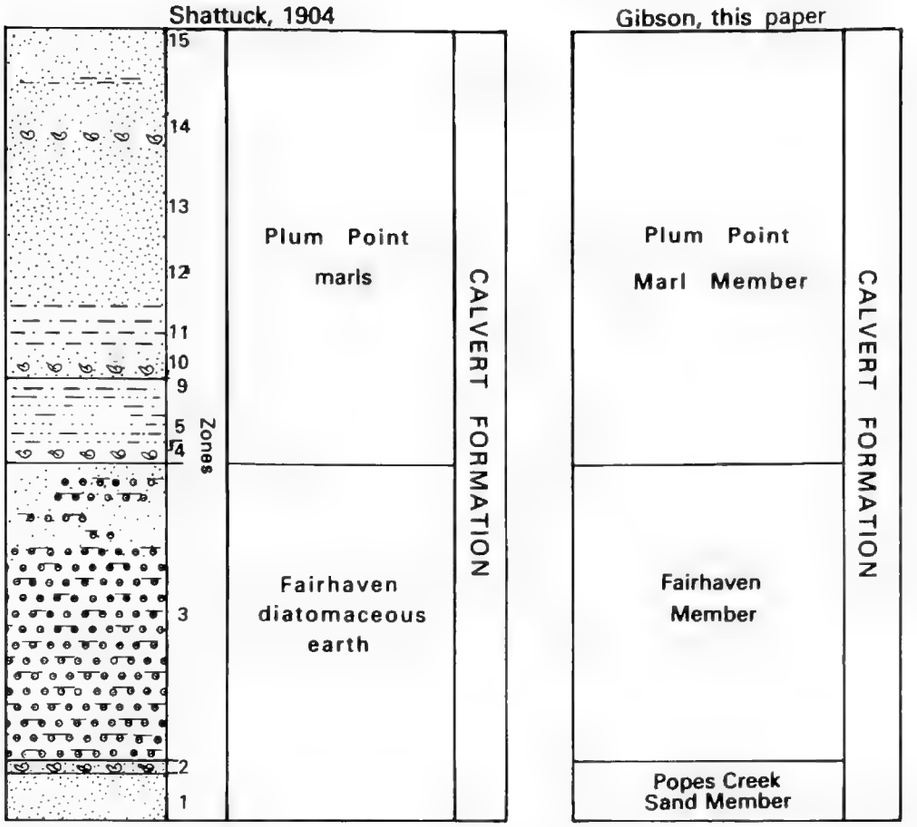


FIGURE 9.—Chart showing beds 1–15 and members of the Calvert Formation according to Shattuck (1904) and as treated in this paper.

found on the Eastern Shore north of Well 220. But there, the middle part of the Calvert is divisible into two facies as seen in wells 224 through 231 (Figures 10–16). The Popes Creek Sand Member continues across the area as a 10 to 20 foot (3 to 6 m) glauconitic sand and gravel, containing quartz and phosphatic pebbles as much as 2 inches (5 cm) in diameter. The Fairhaven Member generally is similar to the beds west of Chesapeake Bay. However, the strata in some of the easternmost wells are less diatomaceous and are composed mostly of green clay and sandy clay. These are interbedded with green and brown clays in the farthest northeast well, 231 (Figures 4: loc. 5, and 10). A significant change is seen in the lower part of the Plum Point Marl Member (equivalent to beds 3 through 9 west of the Bay). Nearest the Bay (to the west, southwest, and northwest of Easton; wells 226, 227, 229 (Figures 4: loc. 11, 9, 6; and 11–13), the beds of green sandy clay containing scattered shells are still present. But in wells to the east of a roughly north-south line through Easton, this interval consists of brown clay and silty clay and gray sand interbeds. The interbedded clay and sand are from ¼ to 2 inches (0.6 to 5 cm) thick, and the thicker sand beds appear to be crossbedded in the cores. Between the brown clay intervals, which may be 30 to 40 feet (9 to 12 m) thick, are intervals of green clayey sand containing scattered shells. This sequence is well developed in Well 224 located approximately 6 miles (9.7 km) southeast of Easton (Figures 4: loc. 10; and 14). The brown clay facies continues northeastward and eastward of Easton (wells 231, 225, and 228; Figures 4: loc. 5, 8, 7; and 10, 15, 16), and appears to be equivalent to the brown clay of the Alloway Clay Member of the Kirkwood Formation of New Jersey as mapped by Isphording (1970).

The upper part of the Plum Point Marl Member (beds 10 to 15 of Shattuck, 1904) is similar over the entire area to the equivalent strata in the

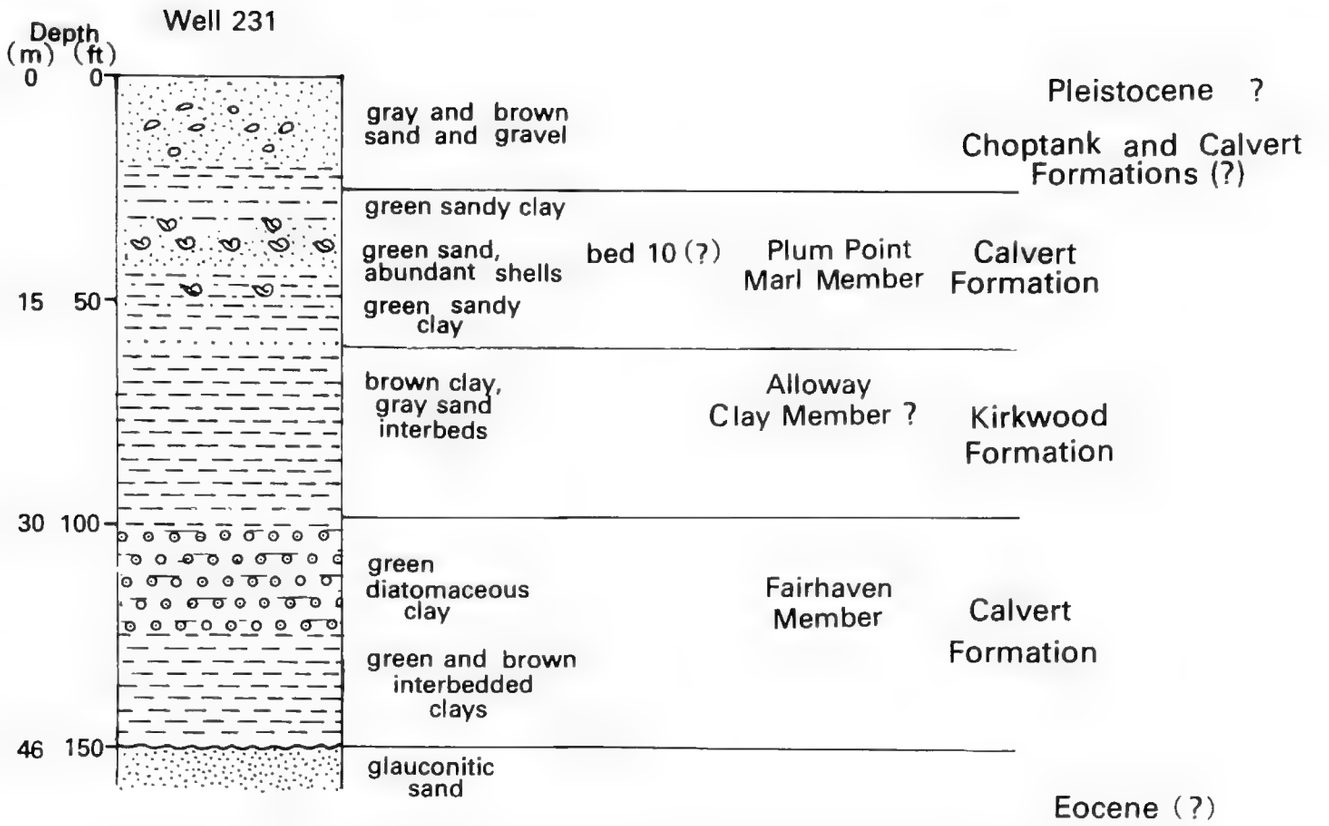


FIGURE 10.—Geologic column for Well 231, near Sudlersville, Queen Annes County, Maryland, showing interfingering of deltaic beds provisionally assigned to Alloway Clay Member of the Kirkwood Formation with inner-shelf sediments of the Plum Point Marl Member of the Calvert.

Calvert Cliffs (beds of green clayey sand and clay and a basal sandy shell bed overlain by intervals of scattered to abundant shells).

Farther east, Talley (1975) described the strata in a well at Greenwood, Delaware (Figure 4; loc. 4), but did not divide the Chesapeake Group into formations. The lower part of the section in this well consists of shelly, glauconitic sand, which Valia, Khalifa, and Cameron (1977) placed in the basal part of the Calvert. I consider the strata to be an eastward extension of the Popes Creek Sand Member. These strata are overlain by dark gray silty clay, probably equivalent to the Fairhaven Member, and then by brown to gray, commonly shelly silt and sand, probably equivalent to the Plum Point Marl Member.

In southwestern New Jersey, Miocene strata of the time-equivalent part of the Kirkwood Formation (Richards and Harbison, 1942), in wells such as NJ1–NJ3 (Figures 4: loc. 1–3; and 17–19), consist of a basal sand overlain by green silty clay, and then by brown clay with thin interbeds of gray sand. The brown clay contains carbonaceous fragments (as long as 5 cm) and generally lacks shells. Above the brown clay sequence, silt and medium sand containing abundant shells crop out near Shiloh (Figure 4: loc. 2) and have been penetrated by the NJ1 well near Cedarville (Figure 4: loc. 3). The stratigraphic sequence is similar to that found in the northeastern part of the Eastern Shore of Maryland. The strata in southwestern New Jersey belong in the Alloway Clay Member as used by Isphording (1970). To the northeast in New Jersey, Isphording reported that the clay grades into his Grenloch Sand Member (herein adopted), which in turn grades northeastward into finely laminated, organic-rich, silty sand of his Asbury Park Member (also herein adopted; former Asbury Clay of Kümmel and Knapp, 1904).

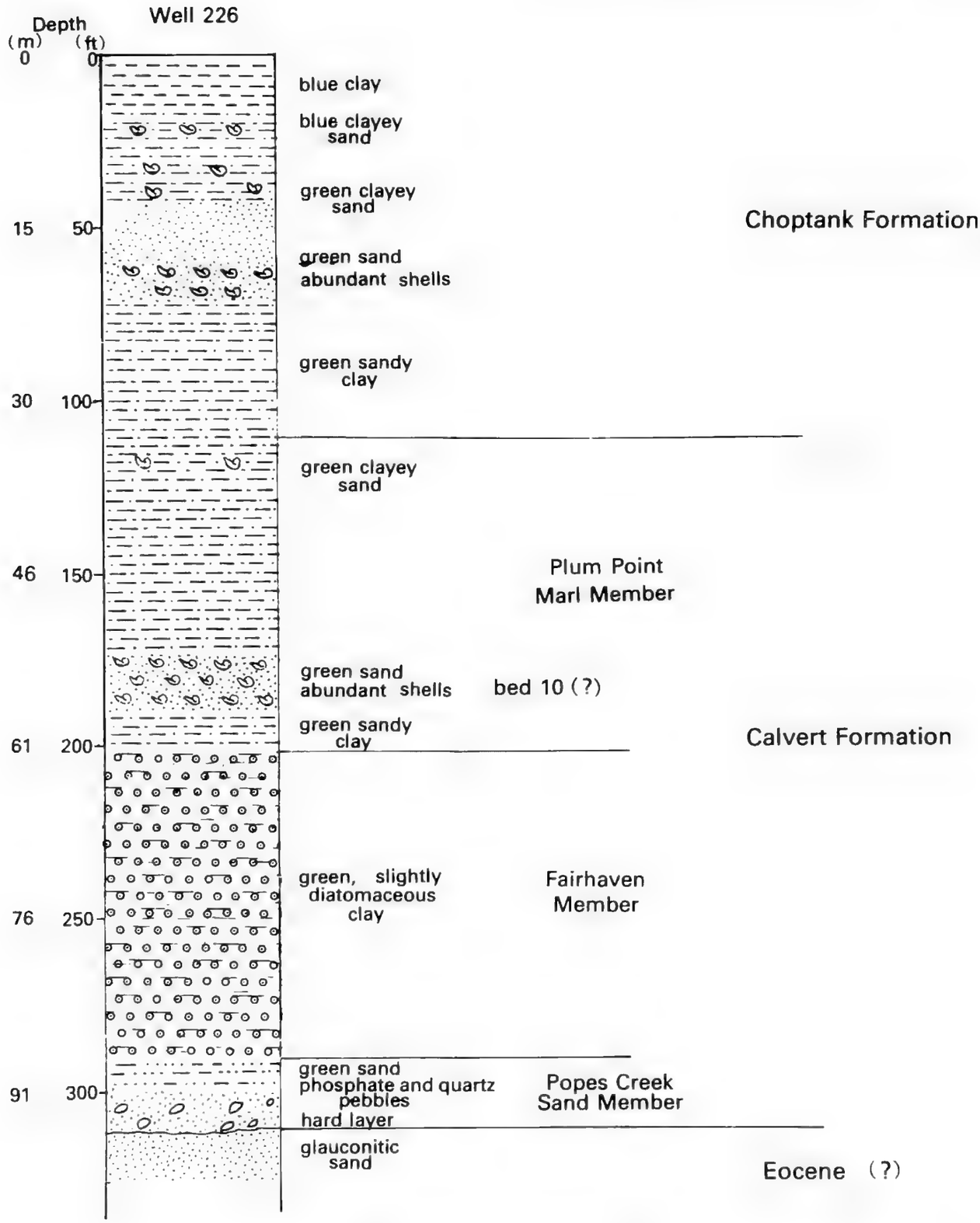


FIGURE 11.—Geologic column for Well 226, near Trappe Creek, Talbot County, Maryland, showing inner-shelf environments in Choptank and Calvert formations.

South of the Calvert Cliffs, the Calvert Formation thins to 110 feet (34 m) in the Oak Grove core hole in northeastern Virginia (Figure 4: loc 19). Here, the basal unit in the Calvert is a 9-foot (2.7-m) pebbly coarse sand to clayey sand containing phosphatized shell fragments. It is overlain by 9 feet (2.7 m) of diatomaceous clay, and above that is 82 feet (25 m) of clayey to silty very

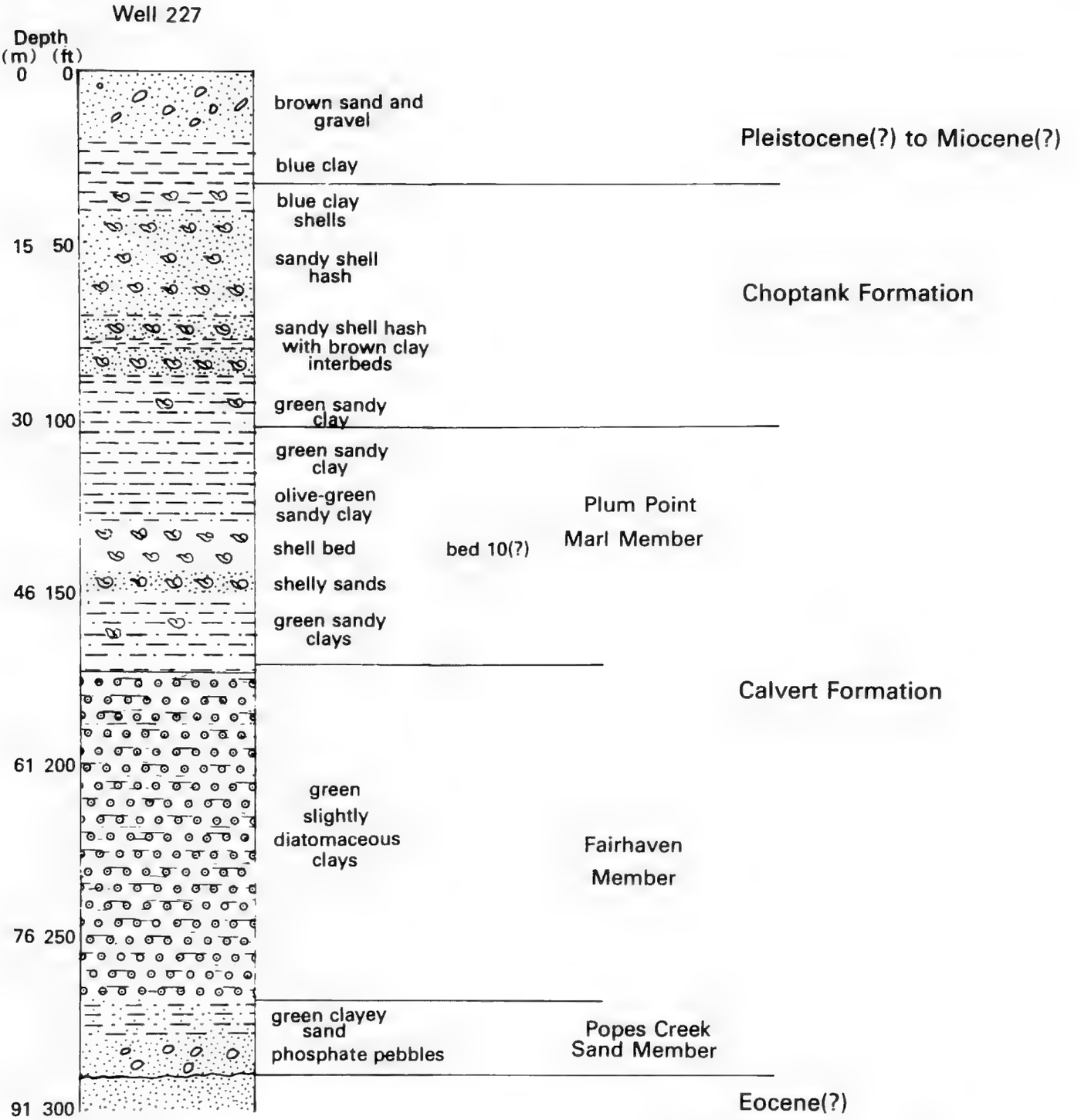


FIGURE 12.—Geologic column for Well 227, near Easton, Talbot County, Maryland, showing basal sands of Popes Creek Sand Member overlain by sediments of inner-shelf environments in remainder of Calvert Formation and small amount of deltaic to prodelta influence in Choptank Formation.

fine sand (Reinhardt, Newell, and Mixon, 1980). The lower sand is considered the equivalent of the Popes Creek Sand Member; the diatomaceous clay, the equivalent of the Fairhaven Member, and the upper 82 feet (25 m), the equivalent of the Plum Point Marl Member. A diatomaceous interval in the upper part of the upper sand contains diatoms equivalent to those of beds 14 and 15 in the Calvert Cliffs (Gibson et al., 1980). Whether the equivalent of the entire Plum Point

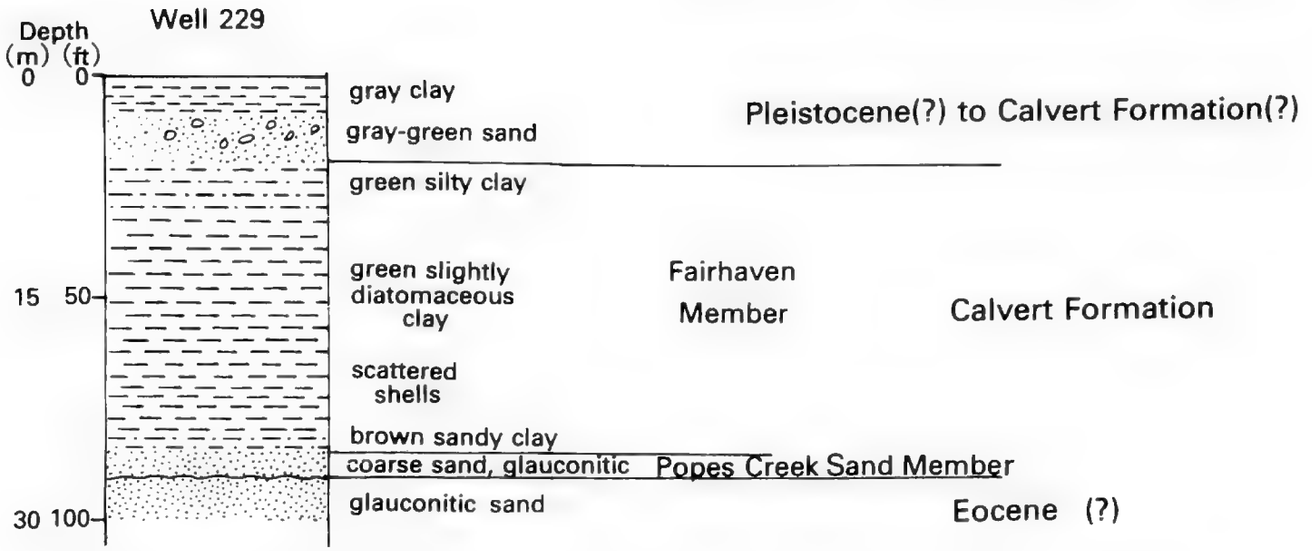


FIGURE 13.—Geologic column for Well 229, near Queenston, Queen Annes County, Maryland, showing coarse sand of Popes Creek Sand Member overlain by diatomaceous facies of Fairhaven Member.

Marl Member is present here is unknown because biostratigraphic control is lacking. However, equivalents of at least part of each member are found. Although marine diatoms and dinoflagellates are present in the Calvert of the Oak Grove core, calcareous fossils are absent here and in most up-dip sections in Virginia. The absence of shells prevents lithologic recognition of the Plum Point Marl Member, although strata of equivalent age are present as determined from the diatoms (Gibson et al., 1980). Lithologically similar sections of the Calvert Formation are found in other parts of the Virginia outcrop belt toward the western edge of the Coastal Plain. Typically, as along the Mattaponi River, the strata contain a basal sand and gravel bed characterized by quartz and phosphatic pebbles and shark teeth and other vertebrate fossils. This is overlain by diatomaceous clay and then by silty clay (Clark and Miller, 1912:126, 135).

In down-dip subsurface sections to the east and southeast in Virginia, such as at Jamestown (Figure 4: loc. 24), green sand and clay containing faunas indicative of open marine to partially restricted marine conditions are found. The Calvert Formation and equivalents are not found on the western part of the Norfolk arch (Figures 1, 3), but are found on or near the arch toward the coast, as in the Moores Bridge Well at Norfolk (Figure 4: loc. 25). Here the upper part of the Calvert section comprises beds of fossiliferous green silty clay characteristic of the formation, but the lowermost 11 feet (3.4 m) is an olive clayey phosphatic sand, similar to that of the Pungo River Formation to the south. Thus, the Norfolk area contains the transition from terrigenous clastic deposition in the Salisbury embayment to largely chemical and bioclastic deposition in the Albemarle embayment to the south.

ENVIRONMENT OF DEPOSITION.—The BG&E Well is the key section for paleoenvironmental interpretation of the Calvert Formation, because it contains the most detailed information in a single continuous section. From this focal point, the regional patterns for each of the members are discussed. Figure 20 shows sand percentage, species diversity of benthic Foraminifera, and percentage of planktonic Foraminifera.

The lowermost strata of the Calvert (Popes Creek Sand Member) accumulated during the transgression of the Calvert sea into the Salisbury embayment. Prior to this, the embayment received widespread glauconitic clay and sand during much of the early and middle Eocene and more restrictively in the late Eocene. In addition, Oligocene seas invaded part of this embayment

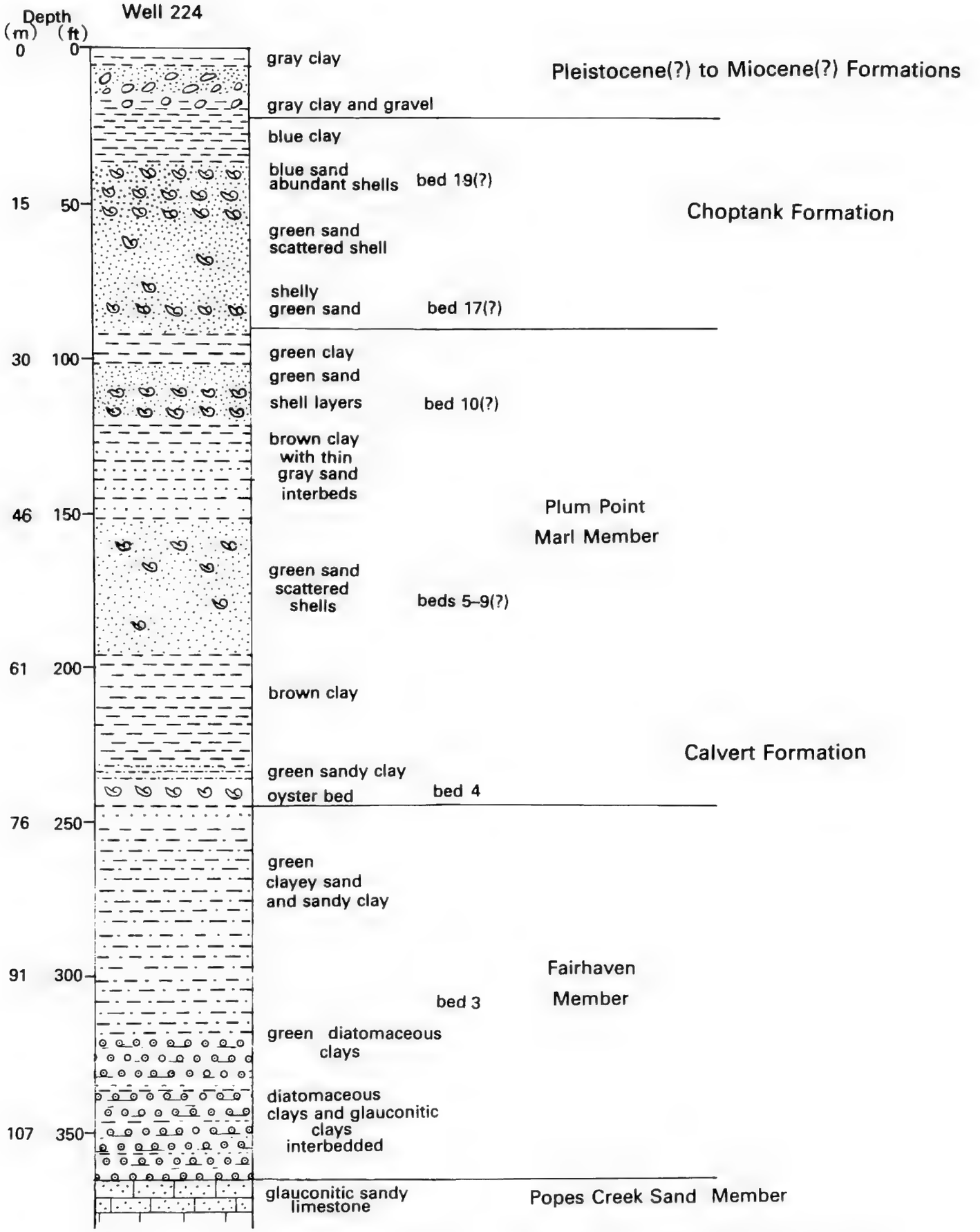


FIGURE 14.—Geologic column for Well 224, southeast of Easton, Talbot County, Maryland, showing deltaic influence in lower and middle part of Plum Point Marl Member and inner-shelf environments in Choptank Formation.

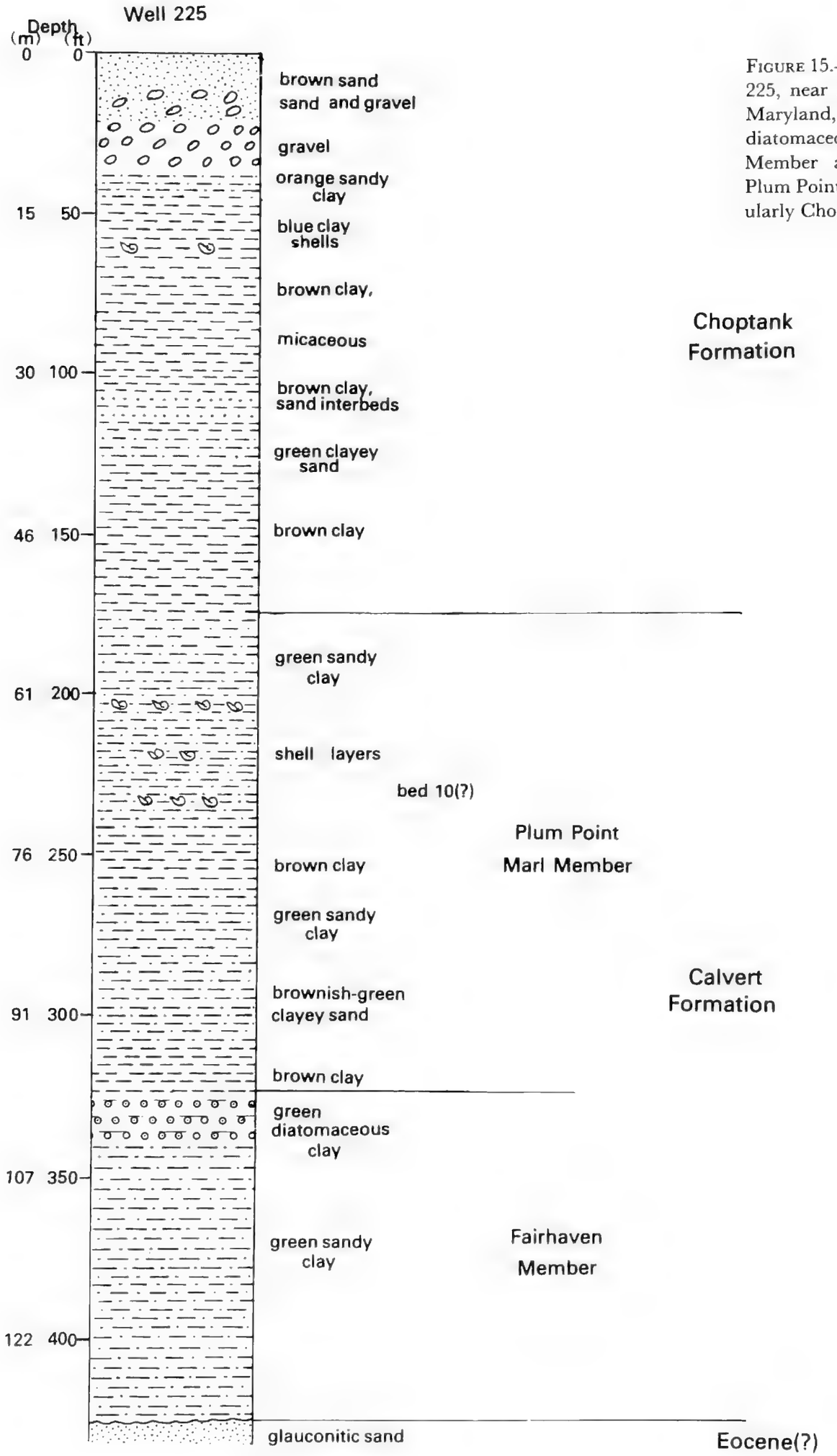


FIGURE 15.—Geologic column for Well 225, near Denton, Caroline County, Maryland, showing lesser amount of diatomaceous beds in Fairhaven Member and deltaic influence in Plum Point Marl Member and particularly Choptank Formation.

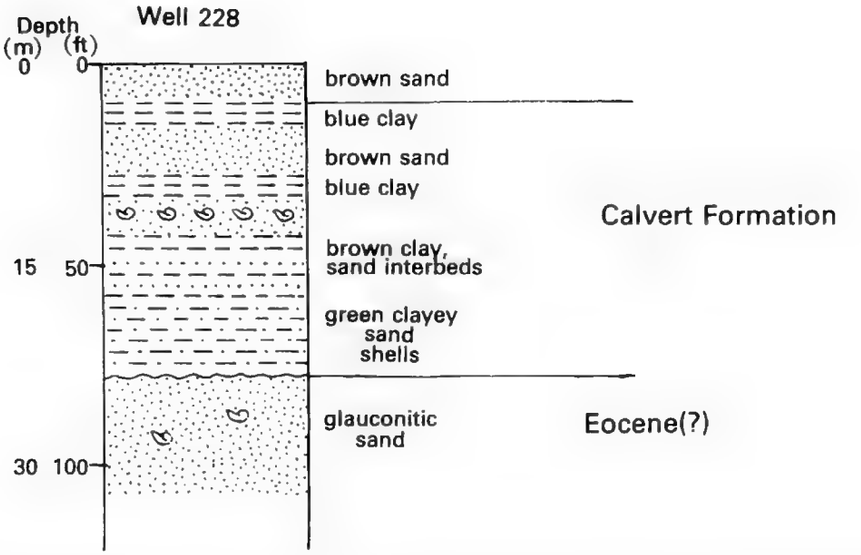


FIGURE 16.—Geologic column for Well 228, near Skipton, Talbot County, Maryland, showing deltaic influence in lower part of Calvert Formation.

(B.W. Blackwelder, pers. comm., 1977; R.K. Olsson, Rutgers University, pers. comm., 1977). The basal transgressive deposit of the Popes Creek Sand Member in the BG&E Well consists of slightly clayey fine to medium sand with pebbles as large as 11 mm, mollusks including *Pecten humphreysii*, and reworked clasts of Eocene sediment containing Foraminifera. The base is composed of 50 percent sand or more. The lowest sample has abundant planktonic Foraminifera (29 percent) and a relatively high species diversity (25). The most abundant benthic species is *Cibicides lobatulus*, which today lives in agitated inner- to middle-shelf environments. Other abundant species include *Valvulinaria floridana*, *Bolivina marginata*, *B. paula*, and *Uvigerina calvertensis*. The lower part of the member suggests deposition in a middle-shelf environment at depths as great as 80 meters and open ocean circulation. In the rest of the member, the percentage of sand decreases to between 25 and 35 percent, and the species diversity remains moderately high, in the low 20s. The planktonic percentage decreases to about 2 percent, and *Valvulinaria floridana* dominates the benthic assemblage. These changes suggest shallowing to near-shore sublittoral depths, probably less than 30 meters. This open marine environment of the Calvert transgression is found over the entire Salisbury embayment, as seen in northern Virginia, Maryland, Delaware, and southwestern New Jersey.

The Fairhaven Member also is lithologically uniform and widespread in the embayment from east-central Virginia to northeastern Maryland. In the BG&E Well, the lower part of this member is of shallow sublittoral deposition, characterized by species diversities of 16 to 21 and planktonic percentages of less than 3. The percentage of sand is less (under 25 percent). Some fluctuations from sublittoral depths as great as 30 meters to either shallower marine or possibly restricted marginal environments are seen upward in the Fairhaven in the intervals with low species diversities of 9 to 12 species marked also by the absence of planktonic specimens; these intervals occur between others that contain higher diversities of 14 to 20 species accompanied by planktonic specimens, although less than 2 percent. The shallow marine environment for this member continues eastward across the basin except for slightly more silty and sandy and less diatomaceous strata to the east and northeast of Easton, Maryland. In Well 231, brown clay is seen within the diatomaceous unit that, together with the slightly increasing clastic content in that area, suggests the possibility of the beginning of deltaic conditions.

The contact between the Fairhaven and the Plum Point Marl members on the western shore

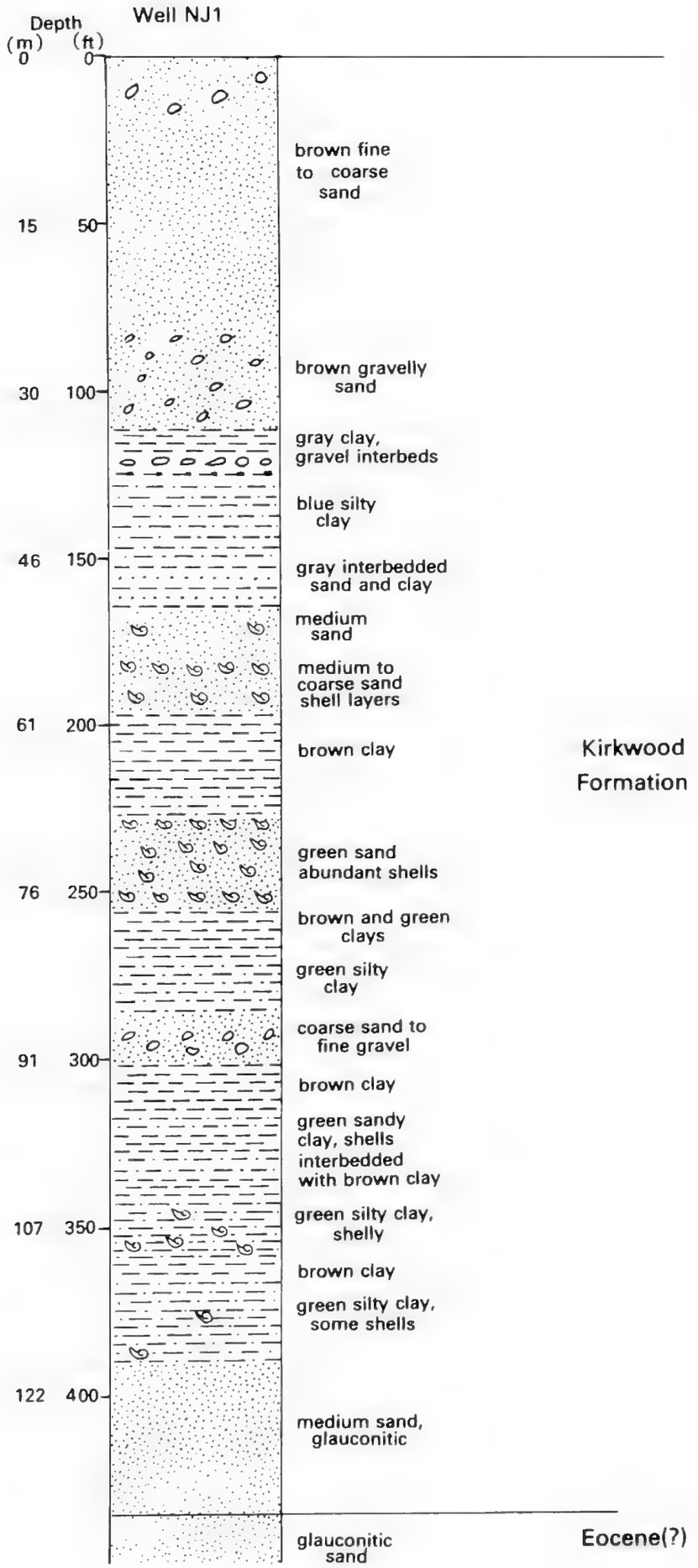


FIGURE 17.—Geologic column for Well NJ1, near Cedarville, Cumberland County, New Jersey, showing interbedding of deltaic and prodelta sediments in the Kirkwood Formation.

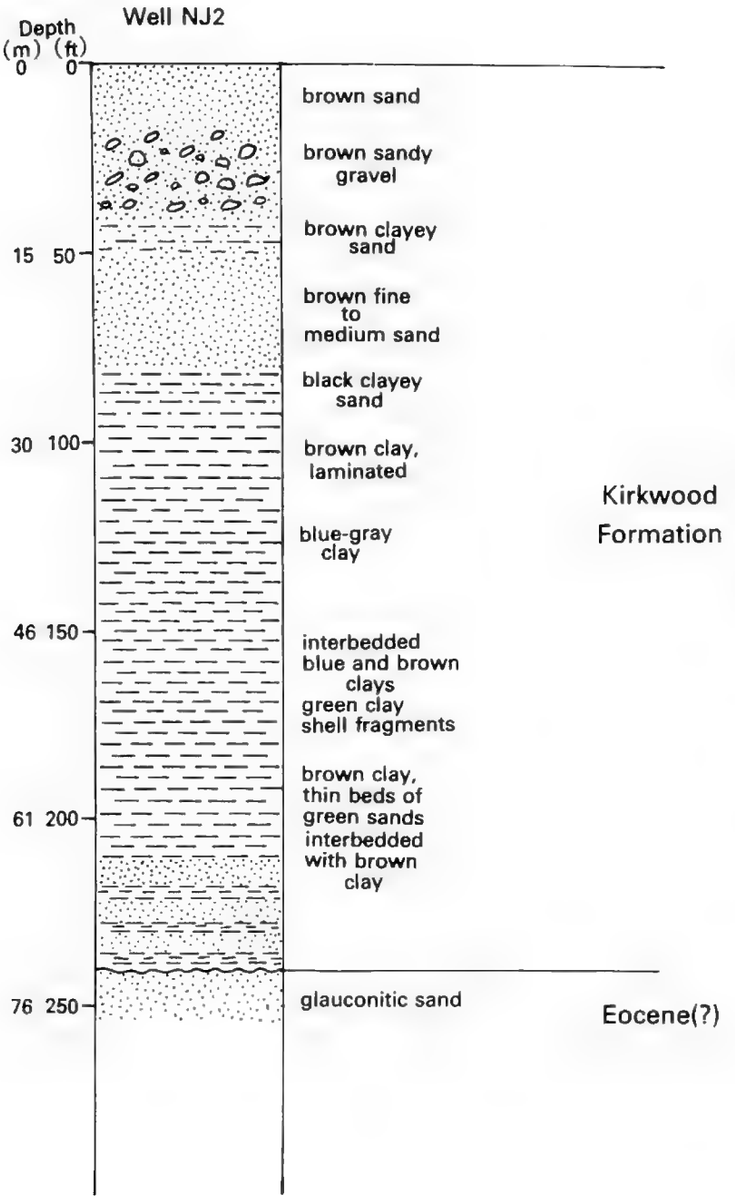


FIGURE 18.—Geologic column for Well NJ2, near Shirley, Salem County, New Jersey, showing largely deltaic section of Kirkwood Formation.

is marked by a disconformity, which may have been produced by either subaerial or submarine environmental conditions. At the base of the Plum Point Marl Member is an oyster (*Pycnodonte percrassa*) bed (bed 4) containing a fairly diverse foraminiferal assemblage of 22 to 29 species (dominated by *Cibicides lobatulus*, *Valvulinaria floridana*, and *Hanzawaia concentrica*) and several percent planktonic Foraminifera in the lower part. This sandy bed (65 to 77 percent sand) is an open marine deposit formed upon an undulating surface, probably in depths of less than 30 meters.

In the BG&E Well, species diversity drops to 13 to 18 in the equivalents of beds 5 to 9 (sample numbers 30–35), planktonic specimens are absent, and the sand content decreases to as low as 2 percent. At the outcrop, molluscan assemblages in these beds are largely bands of *Corbula elevata*. *Valvulinaria floridana*, *Caucasina elongata*, and *Florilus pizarrense* are the dominant benthic species. The faunal characteristics and the high amount of clay suggest deposition in protected to marginal marine environments. The feature that may have sheltered this area is found on the Eastern Shore of Maryland. To the east and northeast of Easton, the interval of beds 5 to 9 contains thick brown clay and thin interbedded sand units, which strongly suggest deltaic influence in the center of

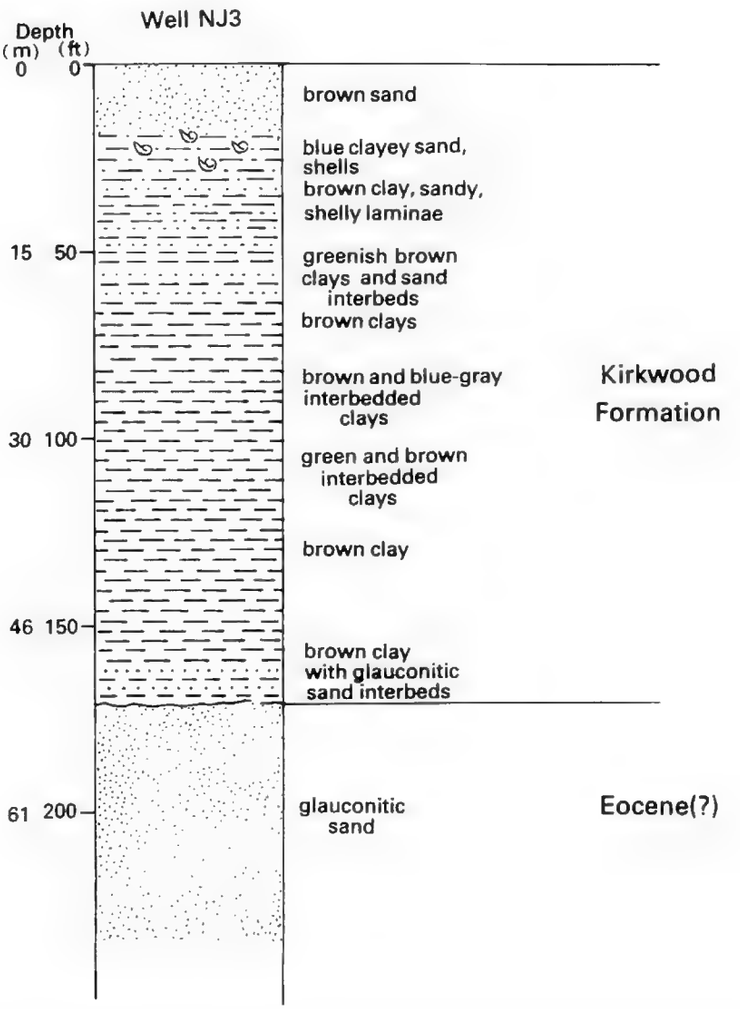


FIGURE 19.—Geologic column for Well NJ3, near Shiloh, Cumberland County, New Jersey, showing largely deltaic sedimentation with marine beds near top of section of Kirkwood Formation.

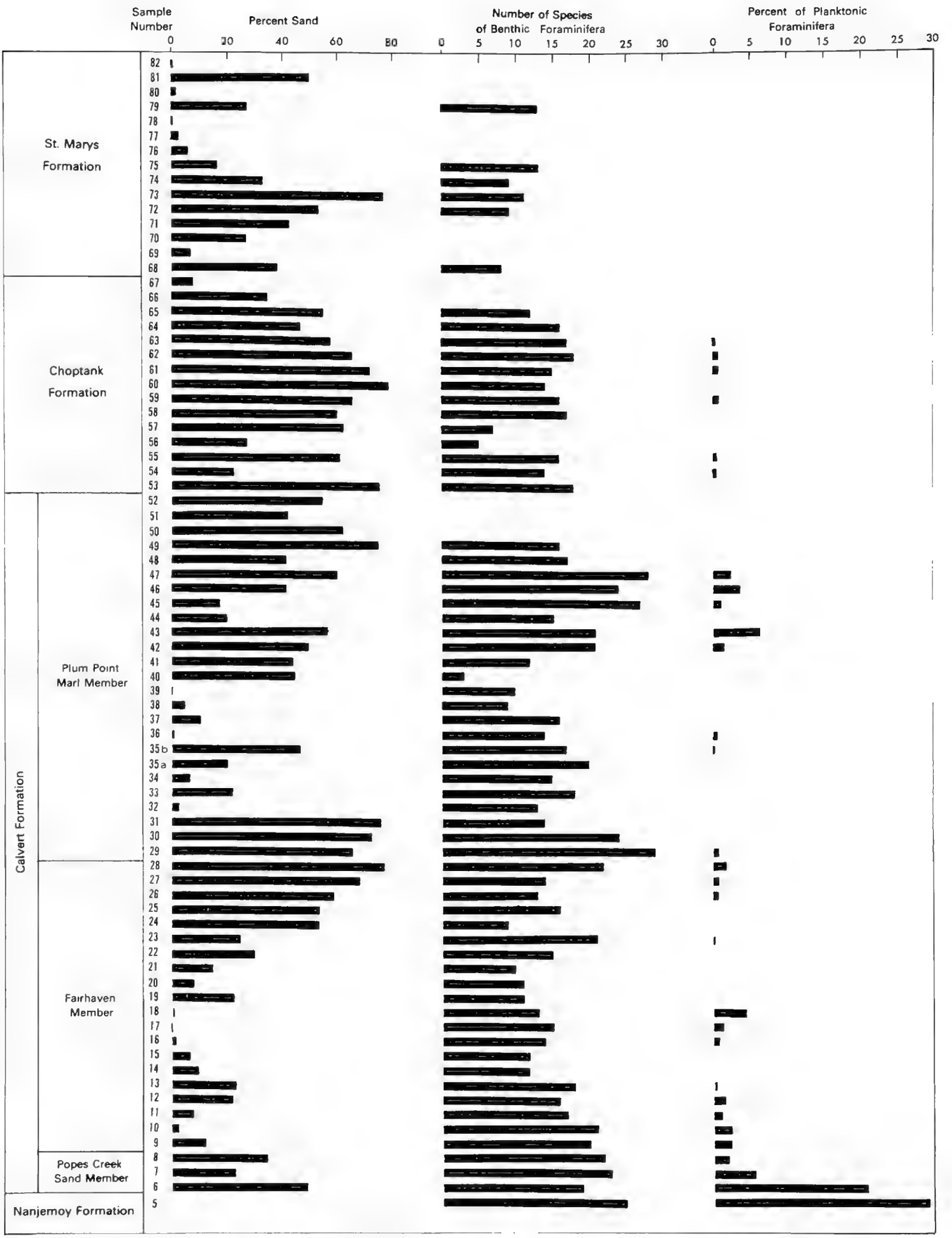


FIGURE 20.—Percentage of sand, number of species of benthic Foraminifera, and percentage of planktonic Foraminifera in total foraminiferal assemblage for samples 5–82 from the Baltimore Gas & Electric Company Well at Calvert Cliffs, Maryland. Location of samples in core is shown in Figure 5.

the Eastern Shore area. The southward outbuilding of the delta into the embayment from source areas in northeastern Maryland, western New Jersey, and Pennsylvania, with the accompanying freshwater influence, appears to have cut off open ocean circulation to the west in Maryland, resulting in an area of fine clastic input and normal to slightly brackish water. Vertebrate evidence to support this interpretation as a protected area is seen in the large number of long-beaked porpoises, typical of estuaries, found in these beds (Whitmore, 1971:32). The area under the influence of the delta is shown in Figure 21. Deltaic environments for the middle Miocene strata on the Eastern Shore were suggested by Gibson (1971). The units of brown clay and silty clay and thin interbeds of crossbedded gray sand as much as 5 cm thick are strongly suggestive of delta-front deposition (Reineck and Singh, 1975:321–338). The interbedded sand and clay do not contain mollusks on the Eastern Shore, but some shells are in brown clay interbeds in southwestern New Jersey. Intervals of fossiliferous green sand and clay occur between the brown clay intervals in wells on the Eastern Shore (Well 224, Figure 14, for example), suggesting that deltaic pulses alternated with more marine prodelta to inner-shelf environments. Isphording (1970) proposed that the Alloway Clay Member of the Kirkwood Formation in southwestern New Jersey accumulated in a sublittoral environment. In my opinion, the presence of thick sequences of carbonaceous brown and dark gray clay interbedded with thin sand suggests a deltaic, delta-front or prodelta, environment. The absence of shells in the brown clay was attributed by Isphording (1970) to solution by sulfuric acid resulting from weathering of the contained pyrite. However, in the cores from New Jersey wells (NJ1–NJ3), the brown clay does not contain shells or molds even though some of the more permeable interbedded sand does. This suggests a primary or early diagenetic absence of shells in the clay and a deltaic rather than marine origin.

Farther east in the Hammond Well (Figure 4: loc. 13), the entire Calvert section is composed of fossiliferous, glauconitic, gray silty clay, characteristic of prodelta and shelf deposition. The area of the Hammond Well appears to be seaward from the deltaic influence, as shown in the paleogeographic reconstruction (Figure 21).

Bed 10 is recognizable across much of the embayment in Maryland as a conspicuous shelly sand containing a high diversity of mollusks (65 species in the Calvert Cliffs, Glaser, 1971:21). West of Chesapeake Bay, it overlies beds 5 to 9 that have low molluscan diversities, and on the Eastern Shore it overlies the brown clay units (Figure 14). Even in southwestern New Jersey a fossiliferous sand is found on top of the brown clay (wells NJ1 and NJ3, and outcrops near Shiloh). Several shell beds containing diverse molluscan faunas are in beds 10 to 15 of the Calvert, and these beds also contain moderately high foraminiferal species diversities. Abundant benthic Foraminifera through this interval include *Valvulinaria floridana*, *Caucasina elongata*, *Cibicides lobatulus*, *Hanzawaia concentrica*, and *Epistominella* sp. Planktonic foraminiferal percentages reach 6 percent. These assemblages suggest reestablishment of open ocean circulation, and deposition on sandy bottoms in depths of less than 60 meters. However, periods of restricted marine conditions in the western part of the embayment are reflected in beds 11 and 15 in the BG&E Well (Figures 5, 20); macrofossils are rare, foraminiferal diversities are low, and planktonic foraminifers are absent. A general increase in sand occurs above bed 11 and continues through the Choptank Formation to beds that indicate restricted environments in the uppermost part of the Choptank and St. Marys formations.

### Pungo River Formation

In the Albemarle embayment south of Virginia (Figure 1) a different sedimentary regime of a low clastic environment resulted in the deposition of phosphatic sand, diatomaceous clay, and carbonate deposits of the Pungo River Formation (Figure 3). As mentioned above, the area of transition between the Calvert and Pungo River formations

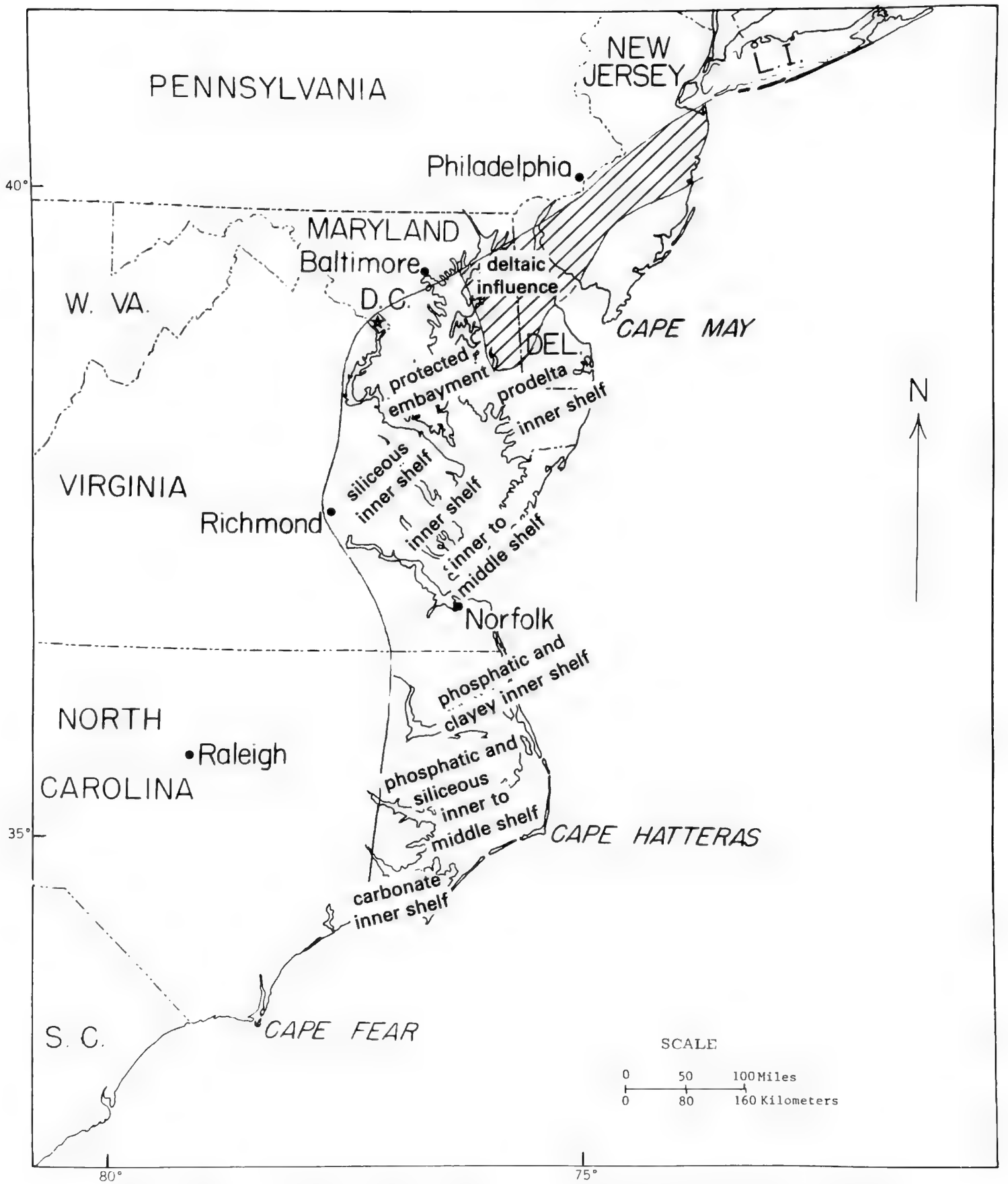


FIGURE 21.—Paleoenvironments postulated for lower half of Plum Point Marl Member of Calvert Formation and equivalent units, showing deltaic influence on Eastern Shore of Maryland and small amount of clastic sediment in the Albemarle embayment in North Carolina. Line indicates western limit of outcrops.

occurs in southeastern Virginia as seen in the Norfolk Moores Bridge Well (Figure 4: loc. 25).

The Pungo River Formation was named by Kimrey (1964) for the sequence of phosphatic sand and clay of middle Miocene age described by Brown (1958). The formation underlies much of the eastern part of the Coastal Plain in North Carolina (Figure 3). No natural outcrops of the formation are known, but it is well exposed in the Lee Creek Mine (Figure 4: loc. 33). The Pungo River is more than 400 feet (122 m) thick in wells drilled on the outer banks in the eastern part of the Albemarle embayment. The middle to inner middle-shelf environments of deposition represented by the formation at its western limits indicate that it originally was more widespread.

The thickest part of the Pungo River Formation in North Carolina is composed of phosphatic and diatomaceous clay, phosphatic sand, phosphatic limestone, and coquina. Kimrey (1965) described the lithofacies in the southern part of the embayment. The beds of clay are light to dark green, and many contain diatoms. The phosphate content varies from less than 1 to nearly 10 percent. The sand is composed of fine to medium quartz and phosphate grains. Phosphate content usually is 10 to 21 percent in bulk samples (Kimrey, 1965:9–14). The phosphatic grains are composed of collophane and are ovate, smooth, glossy, and brown. Sand-sized bone and tooth fragments also are common. Indurated beds of calcareous clay, phosphatic limestone containing dolomite, and indurated shell beds are scattered through the section.

Toward the New Bern arch (southern border of the Albemarle embayment), the upper part of the Pungo River Formation changes to calcareous clay, indurated limestone, phosphatic limestone, and bioclastic debris. North of this area, the equivalent strata are mostly beds of phosphatic and diatomaceous clay with minor phosphatic sand intervals.

I herein propose that this upper carbonate unit, including phosphatic limestone, calcareous clay, and coquina in the southern part of the embayment, be recognized as the Bonnerton Member of the Pungo River Formation. The type section is the AU–1–GRL core hole in the Aurora quadrangle, described by Kimrey (1965:17) (Figures 4: loc. 33; and 22). In this core hole, 32 feet (10 m) of white to light gray-green calcareous sand and phosphatic limestone occur from 120 to 152 feet (37 to 46 m). The name is derived from Bonnerton, Beaufort County, North Carolina, where the unit is typically developed. The Bonnerton is unconformably overlain by the Yorktown Formation; the contact is marked by burrows and small channels containing coarse, black, secondary phosphatic gravels. The lower boundary of the Bonnerton is marked by a change to greenish brown phosphatic sand, which contains phosphatic clay and limestone layers.

Twelve feet (3.7 m) of Bonnerton was exposed in the initial test pit of Texasgulf Inc., in the northeastern part of the Lee Creek Mine site north of Aurora (Figures 23, 24). This includes units 4 to 7 of Gibson (1967). Unit 7 is a yellow-green sandy coquina; unit 6 is interbedded bioclastic debris and phosphatic sand; unit 5 is highly fossiliferous phosphatic limestone; and unit 4 is interbedded phosphatic limestone and phosphatic sand. The lower contact is conformable, and is at the base of the lowest, light-colored limestone bed in Figures 24 and 25. The upper, unconformable contact with the Yorktown Formation is seen in Figures 23, 24, 26, and 27.

As shown by Kimrey (1965, fig. 6), the Bonnerton Member is extensive in the southern part of the embayment and reaches northwestward as far as Bonnerton. To the west of Bonnerton, apparently, this member was completely eroded away. The southernmost locality is in the Croatan Forest area near Great Lake (Figure 4: loc. 36). Here the Bonnerton consists of about 6 feet (1.8 m) of light yellow-green sandy shell hash in Great Lake Well 181. The Bonnerton thus extends at least 40 miles (64 km) north to south. North of Bonnerton, across the Pamlico River, the carbonate facies changes to beds of phosphatic and diatomaceous clay.

The Pungo River strata below the Bonnerton Member are dominantly phosphatic sand and moderately phosphatic to nonphosphatic clay, but include thin interbeds of diatomaceous clay

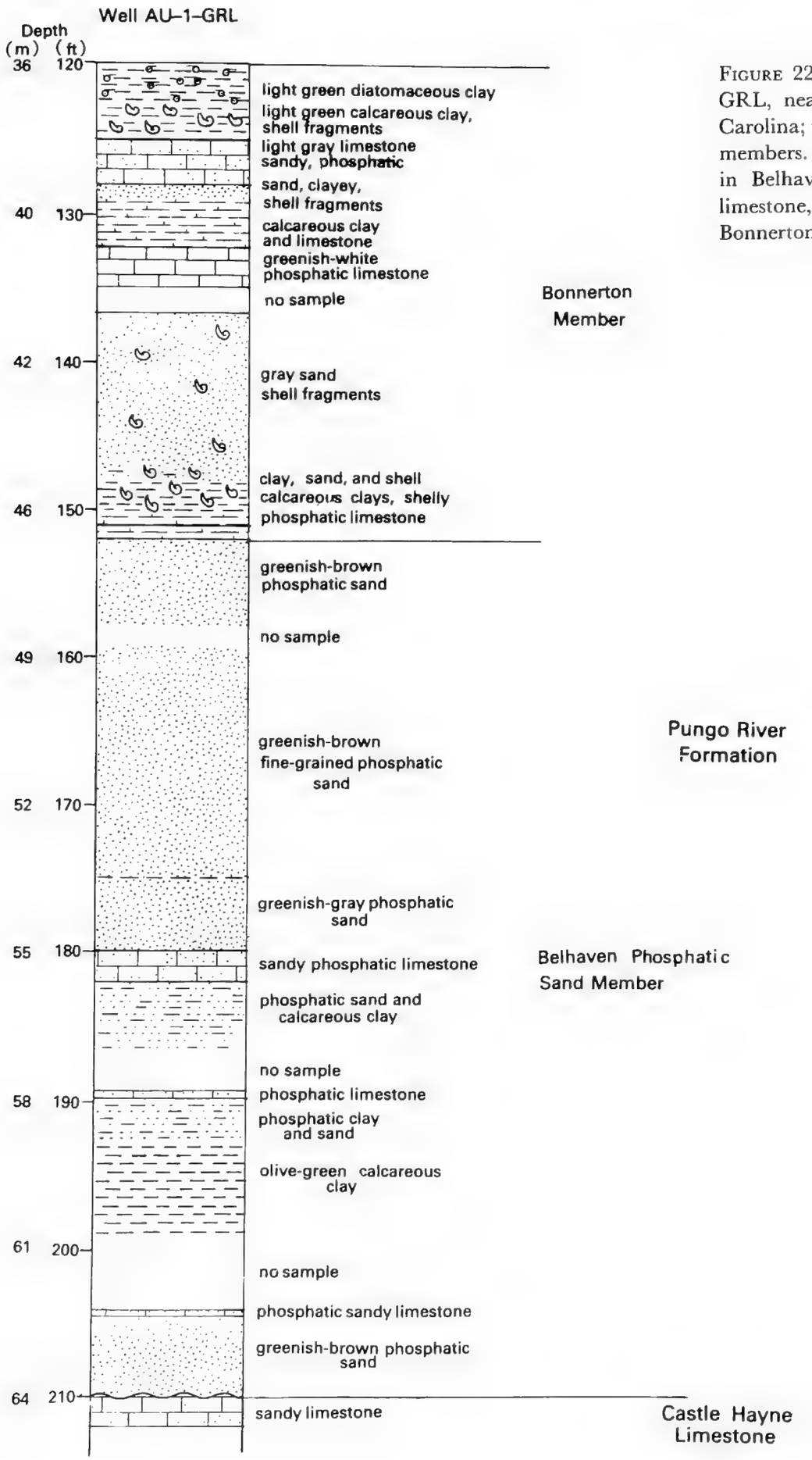


FIGURE 22.—Geologic column for Well AU-1-GRL, near Aurora, Beaufort County, North Carolina; type well for Belhaven and Bonnerton members. Note largely phosphatic sand section in Belhaven Phosphatic Sand Member and limestone, calcareous clay, and shelly sand in Bonnerton Member.

FIGURE 23.—Test pit at Texasgulf Inc. Lee Creek Mine. Water level is at middle of Pungo River Formation with 96 feet (29 meters) of section exposed. Arrow near right margin indicates contact between Pungo River and Yorktown formations in face; close-up of face is shown on Figure 24. Two clean faces in center above lowest bench are in lower and middle parts of the Yorktown Formation. Arrow in upper center indicates boulder beds or unit 7 of Gibson (1967), now considered in lower part of Croatan Formation.

and phosphatic limestone. I herein assign these highly phosphatic beds to the Belhaven Phosphatic Sand Member of the Pungo River Formation. It is so named because it is well developed near Belhaven, Beaufort County, North Carolina (Figure 4: loc. 32). The type section is the same core hole, AU-1-GRL (Kimrey, 1965:18–19; Figure 22), that constitutes the type section of the Bonnerton Member. The Belhaven is 58 feet (18 m) thick (152 to 210 feet (46 to 64 m) in the core hole), and is dominantly medium greenish brown phosphatic sand with some gray-green clay and limestone and dolomite beds. The upper part of this member was exposed in the Lee Creek Mine test pit (Figures 24, 25). The uppermost bed in this member is immediately below the limestone in Figure 25. A slightly indurated, dolomitic, diatomaceous clay bed can be seen at water level in the same figure. The phosphatic sand bed at the top of the Belhaven Member probably is the highest in $P_2O_5$ content over the area. The upper contact of the Belhaven is conformable, but the lowermost part is underlain by the Castle Hayne Formation (Eocene).

Thus, in the southern part of the basin the Bonnerton Member composes most of the section of the Pungo River. To the north near the Lee Creek Mine and northward toward Belhaven, both members are well developed, and northeast of this area most of the formation is composed of the Belhaven Member. Exact biostratigraphic control is not yet available, but the relationship

FIGURE 24.—Largely carbonate beds of the upper part of the Bonnerton Member of the Pungo River Formation overlain by *Placopecten clintonius* beds of the lower Yorktown Formation exposed in north wall of Lee Creek Mine test pit. Arrow indicates unconformity between the two formations. Three channels filled with phosphatic pebbles are visible. Numbers on right border correspond to units used in Gibson (1967).

FIGURE 25.—Contact between dark phosphatic sands of the Belhaven Phosphatic Sand Member and largely carbonate strata of the Bonnerton Member of Pungo River Formation in Lee Creek Mine test pits is at base of lowest light-colored carbonate unit about six feet (1.8 meters) above water level. Two feet (0.6 meters) of diatomaceous clay (unit 2 of Gibson, 1967) of the Pungo River Formation are exposed at water level. Contact between Pungo River and Yorktown formations is at lowest bench, a distance of approximately 20 feet (6 meters) above water level.

indicates that there is a partial to entire facies equivalency between the two members in different parts of the basin.

The lithology of the Pungo River changes northward in the Albemarle embayment. The limestone beds diminish and finally disappear, and the phosphatic sand is thinner, more clayey, and less phosphatic. In the core hole at Gatesville, North Carolina (Figure 4: loc. 27), the Pungo River Formation is only 20 feet (6 m) thick, and consists mainly of yellowish green to greenish brown calcareous, phosphatic, clayey sand. The Pungo River Formation continues northward into the southeastern part of the Salisbury embayment. Here in the Norfolk Moores Bridge Well, the upper 50 feet (15 m) is olive-green silty clay; the lower 10 feet (3 m), dark-olive phosphatic clayey sand.

Gibson (pp. 359–360) demonstrates that the Pungo River strata in the Lee Creek Mine belong to planktonic foraminiferal zone N8 to lower N9 of Blow (1969:229–234) that are of latest early and earliest middle Miocene age. To the northeast, Abbott and Ernissee (pp. 290–293) found Pungo River strata of this age and also of the younger, zone N11 age. Strata of the intervening zone N10 have not been documented in the area. Whether this is because the important index species of this relatively short time zone are absent, or whether this is a time of regression in the embayment represented by a disconformity is unknown.

ENVIRONMENT OF DEPOSITION.—The depositional environments of the Pungo River Formation were discussed by Gibson (1967) and were determined on the basis of the foraminiferal assemblages (Gibson, 1968). Gibson concluded that the beds of phosphatic sand of the Belhaven Member formed on the middle to outer shelf (approximately 100- to 200-m water depth). The carbonate and phosphatic clay beds in the Bonnerton Member formed on the middle to inner

FIGURE 26.—Unconformable contact (arrow) between Pungo River (light-colored) and Yorktown (dark-colored) formations in the test pit of the Texasgulf Inc. Lee Creek Mine. Channels in bryozoan hash bed at top of the Bonnerton Member of the Pungo River Formation are filled with phosphate pebbles. Lowermost Yorktown strata contain abundant *Placopecten clintonius* and medium sand to cobble-sized phosphate grains. Close-up of channel at left is shown in Figure 27.

shelf (150 m to less than 70 m in the uppermost bed, Gibson and Buzas, 1973:232).

In addition to the faunal evidence, the nature of the phosphatic sand, the organization of its beds extending tens of kilometers, and the interbedded limestone and diatomaceous clay led Gibson (1967:638, 642) to consider this phosphate deposit a primary deposit from seawater. The framework of deposition, particularly the depth of water, fit the Kazakov (1937) hypothesis of inorganic precipitation that has been used to explain numerous large phosphatic deposits. A weakness in this hypothesis is that the phosphate mineral found in these deposits does not commonly form in the laboratory (McConnell, 1958). The presence of large amounts of phosphatic fish bones and teeth may indicate that the postulated upwelling or mixing of currents and resultant high productivity biologically concentrated unusual amounts of phosphatic material in the sediments. Another possible method is phosphate replacement of existing carbonate material. Although replacement may explain the thin layers of phosphate in the top of underlying carbonate units, such as those in the Castle Hayne Formation, this origin for the major deposit has serious complications, because the molluscan fossils in the phosphatic sand are phosphatic internal molds. This manner of preservation indicates that the shell was still present when the phosphate material was introduced and that the shell was filled, not replaced. The ovoid shape of many of the phosphate pellets is similar to that of fecal pellets; these pellets may have formed by the

addition of phosphate. We do not know the exact genesis of these deposits, but evidence to date strongly indicates that they are primary deposits from a middle- to outer-shelf environment.

Another characteristic of the Pungo River strata is the small influx of coarse clastic sediments. The offshore deposits are primarily phosphatic sand and diatomaceous clay that become more calcareous landward, indicating little clastic influx into the Albemarle embayment from that direction. Thus, the uplift of the Appalachians that affected the northern part of the Coastal Plain at this time, as seen in New Jersey, is not evident here.

The presence of clinoptilolite, volcanic glass, shards, and cristobolite in the Pungo River Formation led Rooney and Kerr (1964) and Gibson (1967) to suggest a volcanic influence in the depositional area. The importance of this influence still is largely unknown. However, this time interval is characterized by unusual deposits all along the Atlantic Coast. The deposits include diatomaceous clay containing shards and clinoptilolite in the Fairhaven Member of the Calvert Formation in Maryland (Taliaferro, 1933:28; Glaser, 1971:23) and Virginia (Reinhardt, Newell, and Mixon, 1980); phosphatic and diatomaceous clay and sand in North Carolina; and montmorillonite, cristobolite, and attapulgite in South Carolina and Georgia (Ernissee, Abbott, and Huddlestun, 1977). The only region apparently unaffected at this time is New Jersey, which was under a strong deltaic influence. The possibility was raised by Gibson and Towe (1971) that widespread siliceous deposits of a short timespan could be a result of marine volcanism, which influenced productivity through the addition of nitrogen and phosphorus into the water column. The increase in the levels of these nutrients, in addition to the added silica, could result in abundant siliceous organisms in the area, and thus increased deposition and enhanced preservation. Questions have been raised about the role of volcanism in these areas (Weaver and Wise, 1974;

FIGURE 27.—Unconformable contact between *Placopecten clintonius* beds of Yorktown Formation and bryozoan hash beds of the Bonnerton Member of the Pungo River Formation. Coarse phosphate pebbles fill channels in top of Pungo River; generally finer pebbles occur in shell bed of the Yorktown. Pen giving scale is 5 inches (12.7 cm) long.

Gibson and Towe, 1975). Weaver and Wise stressed the finding of siliceous organisms as proof that volcanic influence was not present or important. However, this missed the main point of the model proposed by Gibson and Towe (1971) that the volcanism largely would cause increased productivity of siliceous organisms in many environmental settings. The finding of these unusual deposits over a relatively short timespan of a few million years requires some explanation. One new piece of evidence, which indicates volcanic influence in the area, is the presence in the Pungo River Formation of large pieces of pumice, as much as 6 inches (15 cm) in diameter. These pieces have been uncovered during washing of the ore at the Lee Creek Mine. The pumice currently is being analyzed to determine the possible origin and significance.

### Choptank Formation

The Choptank Formation was named by Shattuck (1902) from exposures along the Choptank River on the Eastern Shore of Maryland. Most subsequent work has been more concerned with the extensive exposures along the Calvert Cliffs on the western shore of Chesapeake Bay. The outcrop thickness varies from 45 to 55 feet (14 to 17 m) (Shattuck, 1904, pls. xxx, 5). The continuous BG&E core contains approximately 60 feet (18 m) of Choptank. Thicker sections occur in the subsurface to the east. The Hammond Well on the Eastern Shore of Maryland (Figures 4: loc. 13, and 6) contains 125 feet (38 m) (Anderson, 1948:19), and 150 feet (46 m) was found in Well 220 to the southwest of the Hammond Well (Figures 4: loc. 12 and 7); this appears to have been in the axis of the embayment during Choptank time.

The Choptank Formation in outcrop characteristically is quartz sand and silt, shelly in many places, with lesser clayey intervals and indurated limestone layers. The BG&E Well contains mostly muddy and silty fine sand (Figure 5; generally 50 to 70 percent sand, Figure 20). Minor silt and clay intervals are present, along with two indurated layers. Two intervals contain numerous molluscan shells (beds 17 and 19 in outcrop), and shells occur sparsely in the rest of the formation. Outcrops in the type area of the Choptank are similar to those found west of the Bay. However, two wells on the Eastern Shore contain a different facies of the Choptank Formation. Well 225 (Figure 15), northeast of the type area, contains mostly brown micaceous clay interbedded with scattered shell hash; the rest is green to blue, shelly, clayey sand containing quartz and phosphate pebbles, thickly interbedded with brown clay and gray sand laminae. In Well 227 (Figure 12), green sandy clay containing shells and sandy shell hash composes most of the formation, but the middle part contains interbedded shell hash and brown clay. To the southeast, in the Hammond Well (Figure 6), the Choptank is composed of limy, sparsely glauconitic, shelly, medium sands.

Shattuck (1904) divided the Choptank Formation into a series of zones (here termed "beds") numbered 16 through 20. As in Shattuck's division of the Calvert Formation, these zones are locally distinguishable by lithologic, not biostratigraphic, characteristics. One zone, was defined, however, by the abundance of fossils, particularly mollusks. Gernant (1970) mapped these "zones" in the Choptank Formation and redefined them as lithologic members. The nature of the upper contact of the Choptank is in dispute because Blackwelder and Ward (1976:12, 15) placed Gernant's uppermost member, the "Conoy," into an overlying unit, which they informally referred to as the "Little Cove Point" unit.

The distribution and thickness of the Choptank Formation is considerably restricted compared to the underlying Calvert Formation. The known distribution extends into northeastern Virginia as shown in Figure 28. In the Oak Grove core hole (Figure 4: loc. 19), located at approximately the known southern limit of the Choptank, slightly diatomaceous clay and silt were found that correlated with beds 18 and 19 of the Choptank Formation (Gibson et al., 1980). The Choptank strata of bed 18 and 19 age in the Oak Grove core sit upon the upper part of the Calvert Formation, signifying the southward disappearance of the

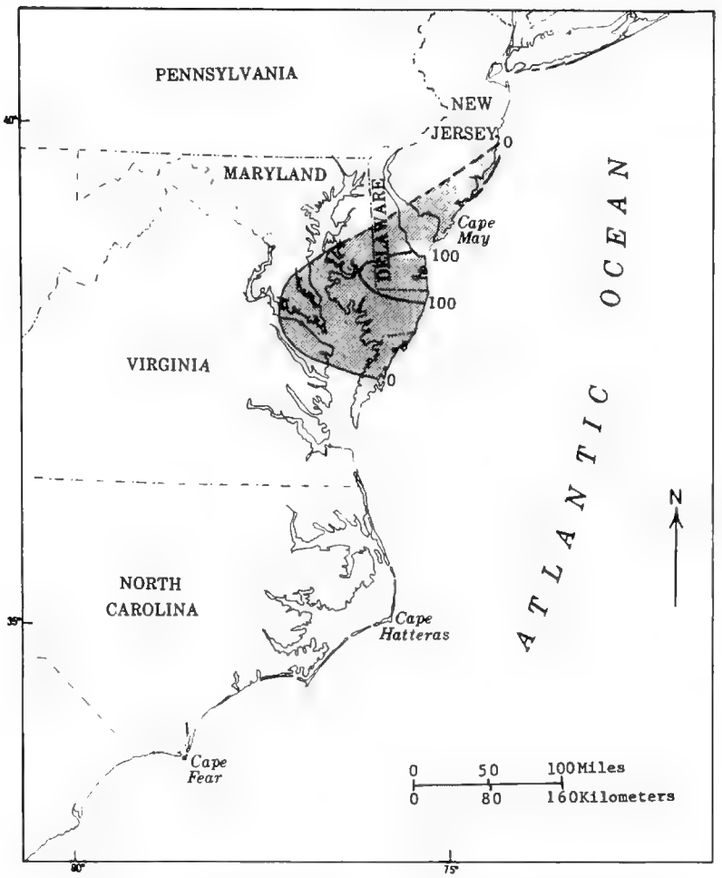


FIGURE 28.—Isopachous map of the Choptank Formation and equivalent units (middle Miocene). Contours are in feet; contours are indicated by dashed lines where locations are approximated (modified from Gibson, 1970).

lower beds 16 and 17 of the Choptank that still are present at the Nomini Cliffs on the Potomac River. No indication of Choptank-age strata has been found in southern Virginia and North Carolina. The northern extent of the formation in New Jersey is uncertain because Richards and Harbison (1942) treated the Calvert and Choptank formations as a single unit.

Because the Choptank Formation was deposited in very shallow marine water, its present distribution probably closely reflects the original extent of the Choptank sea (Figure 28). The distribution was restricted by uplift in various areas, including the Albemarle embayment in North Carolina, causing a markedly reduced areal extent of the Choptank seas.

ENVIRONMENT OF DEPOSITION.—The Choptank Formation was deposited mostly in shallow marine water (Gibson, 1962:63). Gernant (1970:45–52) also proposed that environments were less than 60 meters deep for the formation as a whole, but they were less than 25 meters deep, and possibly marginal marine, for some beds. Foraminiferal assemblages in the BG&E Well support these interpretations. Foraminiferal species diversity is less than 20 in all samples (most samples contained about 15), and the planktonic foraminiferal content varies from zero to less than 1 percent (Figure 20). These measures of foraminiferal abundance are similar in about 100 samples examined from other localities. On the Eastern Shore in the type area, similar shallow water deposits persist and shell hash is common. Gernant (1971:28) suggested that here much of the formation was deposited in shallower water than that west of Chesapeake Bay. The sediments usually are more than 50 percent sand, which, along with the foraminiferal data, suggests deposition in open shallow marine water of 15 to 30 meters depth or less.

On the Eastern Shore, evidence of deltaic influx into the eastern and northeastern part of the Choptank Formation is present in the subsurface. Well 225 (Figures 4: loc. 8, and 15) contains thick intervals of brown micaceous clay and interbeds of pebbly shell and gray sand that suggest delta-front deposition. To the southwest, Well 227 (Figures 4: loc. 9, and 12), farther away from the delta front, contains mainly shell hash and interbeds of brown clay in the middle part. In the Hammond Well (Figures 4: loc. 13, and 6). Choptank strata are limy and shelly medium-grained sand containing small amounts of glauconite, indicating shallow sublittoral deposition. The green shelly sand and shell hashes in wells 224 and 226, and the Hammond Well suggest that these strata accumulated in prodelta or inner-shelf environments; they mark the southern limit of deltaic influence (Figures 4, 29). The deltaic outbuilding at this time on the Eastern Shore did not significantly influence deposition in the western part of the embayment, because diverse molluscan, ostracode, and foraminiferal assemblages dominated by *Cibicides lobatulus*, *Bolivina paula*, *Valvulinaria floridana*, and *Buliminella elegantissima* indicate shallow open marine water of normal

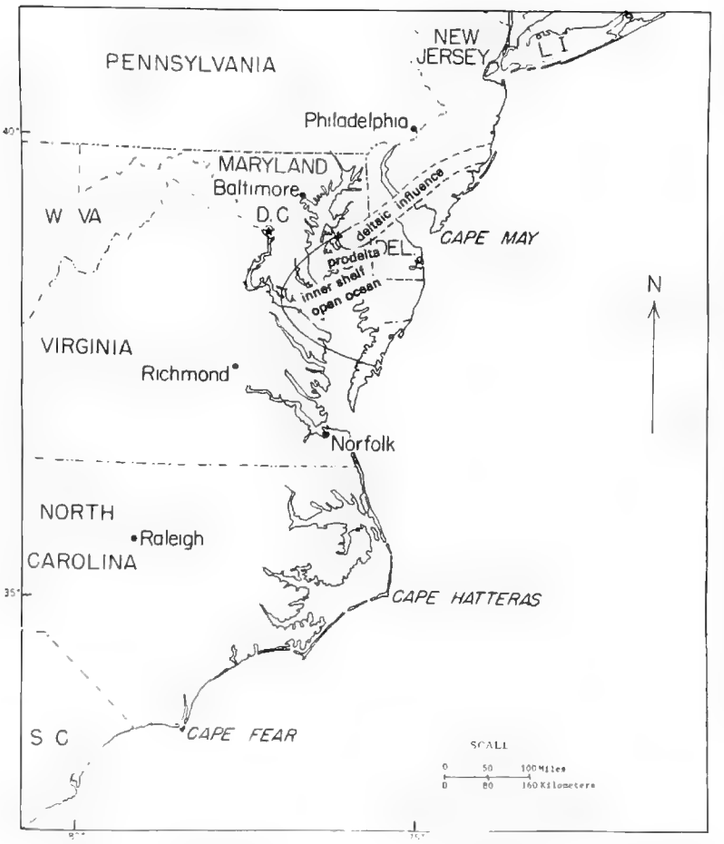


FIGURE 29.—Paleoenvironments postulated for the Choptank Formation and equivalent units, showing deltaic influence on Eastern Shore of Maryland and open marine shallow shelf in remainder of embayment. Line indicates limits of formation; line is dashed where limits are inferred.

salinity. More open access to the Atlantic Ocean must have prevailed at that time than in middle Calvert time.

## St. Marys Formation

The St. Marys Formation was named from exposures in St. Marys County, Maryland, particularly those along the St. Marys River near the city of St. Marys (Shattuck, 1902). Other outcrops in St. Marys County are known along the southern bank of the Patuxent River and along the western shore of Chesapeake Bay. Outcrops also extend farther north along Chesapeake Bay into Calvert County. A few outcrops of equivalent age strata are in northern Virginia (Ward, pers. comm., 1971); otherwise, the St. Marys in northern Virginia and on the Eastern Shore is known only in the subsurface. The St. Marys Formation is geographically restricted as is the underlying Choptank Formation in Maryland and northern Virginia (Figure 30).

Shattuck (1904:lxxxv) divided the St. Marys into lithologic "zones" 21 to 24; the lower three zones are exposed in southern Calvert County and the upper one crops out in St. Marys County. A total thickness of 74 feet (23 m) for the four units combined was estimated (Shattuck, 1904: lxxxv), but no continuous outcrop section or sections exist. As much as 185 feet (56 m) is now known in the Hammond Well (Anderson, 1948:19) on the Eastern Shore (Figure 6). The outcropping St. Marys west of Chesapeake Bay comprises beds of blue clay, sandy clay, and clayey sand, commonly containing shell layers. Clay is more abundant than in the underlying Choptank Formation. The lower percentage of sand is typified in the BG&E Well, where sand is

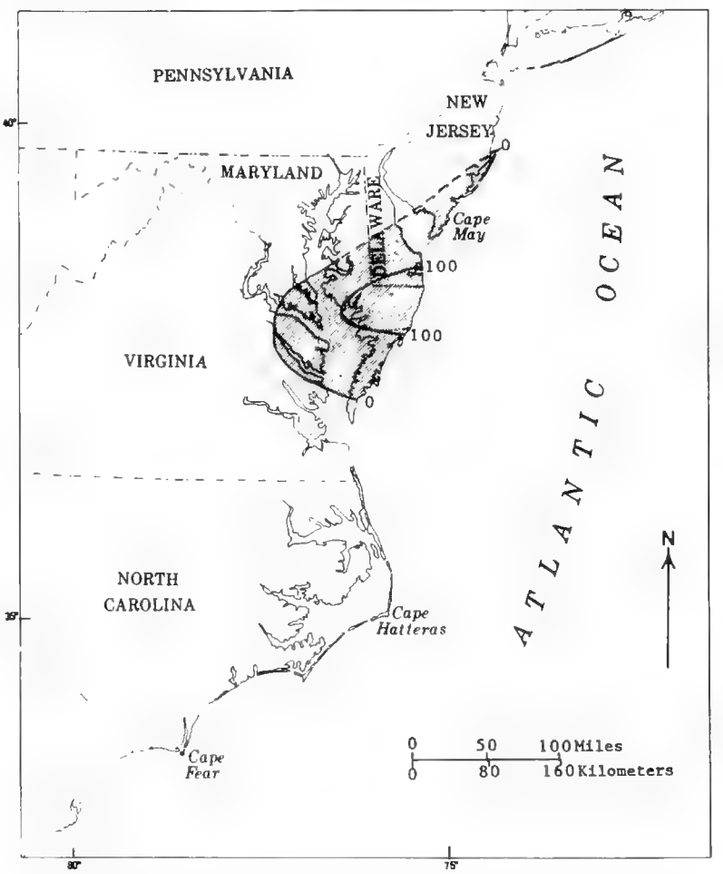


FIGURE 30.—Isopachous map of the St. Marys Formation and equivalent units (upper Miocene). Contours are in feet; contours are indicated by dashed lines where locations are approximated (modified from Gibson, 1970).

less than 50 percent in the lower part of the formation and less than 10 percent in the middle and upper parts (Figure 20). In the Hammond Well (Figure 6) on the Eastern Shore, the strata placed in the St. Marys are coarse sand and fine gravel containing shell fragments and some glauconite.

Environment of Deposition.—The St. Marys Formation was deposited in a shallow-marine to marginal-marine basin (Gibson, 1962:65; Gernant, 1971:28–30). Gernant (1971) suggested a shallow-subtidal to marginal-marine origin for all beds. In the BG&E core, the low species diversity of 13 or less, dominance of the assemblages by *Buliminella elegantissima*, *Buccella mansfieldi*, and *Cibicides lobatulus*, and the absence of planktonic foraminifers in most samples suggest depths of less than 30 meters for the marine beds. Organic rich brownish gray and dark gray clay beds containing only 2 percent sand or less suggest brackish to restricted marine deposition for at least part of beds 21 and 23. Bed 24, which constitutes the upper part of the St. Marys along the St. Marys River, contains richly fossiliferous sand and some interbedded nonfossiliferous clay. The shelly units are dominated by a relatively few molluscan species, primarily gastropods. Foraminiferal species diversities range from 15 to 20; the benthic assemblages are dominated by *Buccella mansfieldi*, *Florilus pizarrense*, *Buliminella elegantissima*, and *Quinqueloculina seminula*. Planktonic foraminifers usually form less than 1 percent of the assemblages, although one sample contains 9 percent. These foraminiferal assemblages suggest deposition in shallow marine conditions at depths of less than 30 meters. The nonfossiliferous clay probably represents restricted marginal-marine conditions.

The St. Marys strata in the Hammond Well on the Eastern Shore consist of coarse sand and fine gravel containing shell fragments. In New Jersey, the St. Marys fossils occur in beds followed by thick sequences of coarse clastic deposits (Richards and Harbison, 1942:171), which Isphording and Lodding (1969) and Isphording (1976) considered to overlie the Kirkwood Formation conformably. These medium- to coarse-sand and gravel beds, usually referred to the Cohansey Sand, suggest, as do those of the Hammond Well, that clastic debris was carried in by the same delta system that had been building in the area since middle Calvert time. The large influx of coarse clastic deposits at this time indicates uplift of the Appalachian source area as Gibson (1971) suggested. In the embayment to the west of this rapidly prograding delta sequence, open ocean circulation was cut off for significant periods of time, and deposits of restricted marine to brackish environments were formed as seen in beds 21 and 23 and part of 22. Open marine circulation must have been temporarily re-established during deposition of parts of bed 24 slightly to the south.

## "Virginia St. Marys" Beds

The "Virginia St. Marys" beds represented a transition in Miocene depositional patterns in the Salisbury embayment as the axis of depositon moved south of that found in the Choptank and St. Marys formations. Mansfield (1943) divided the St. Marys outcrops in Virginia into three units. Mansfield questionably correlated the lowermost, stratum A, with beds 21 and 22 of the St. Marys in Maryland. Stratum A is an unfossiliferous silty clay found only in northernmost Virginia, and is presumably a marginal-marine or nonmarine unit occurring at the southern extremity of the St. Marys Formation. The overlying unit, termed "zone 1" by Mansfield (1943:6) was correlated with beds 23 and 24 of the St. Marys in Maryland. Zone 1 extends farther south than stratum A, reaching approximately the Rappahannock River. Mansfield believed that his highest unit, zone 2, was younger than the fossiliferous St. Marys in Maryland. The distribution of zone 2 reflects the continued southward shift in basin location; the zone as reported by Mansfield (1943;6) reached no farther northward than the Rappahannock River, and it extended southward to the James River in southern Virginia. My subsequent field investigations show that zone 2 extends to northern Virginia at the Nomini Cliffs

on the Potomac River and even farther south into northeastern North Carolina along the Meherrin River in the vicinity of Murfreesboro (Figures 4: loc. 28; and 31). The foraminiferal assemblage of zone 2 strata at the Nomini Cliffs indicates a shallow marine environment. Even shallower marine or marginal-marine deposits probably continued into southern Maryland. Most of these strata probably have been stripped by erosion, but possibly some marine and probably some marginal-marine deposits of this age may be found as outliers in Maryland (Stephenson and MacNeil, 1954).

As Mansfield's zone 2 of the St. Marys is younger than the type St. Marys, and occurs largely in Virginia, I have used the informal term "Virginia St. Marys" beds to differentiate zone 2 beds from the type St. Marys Formation in Maryland (Gibson, 1971). Because the geographic distribution and lithology of the "Virginia St. Marys" beds (Figure 31) are similar to those of the immediately overlying Yorktown (Figure 32), and because they occupy the same depositional basin, I placed the "Virginia St. Marys" beds strata into the basal part of the Yorktown Formation (Gibson, 1971). Although the "Virginia St. Marys" beds are without question slightly older than the type Yorktown, the units have a similar genesis. This placement of these strata is similar to that by Olsson (1917:3) who recognized an intermediate fauna between the St. Marys and Yorktown faunas and termed this the "Murfreesboro" stage. Mansfield (1943) and Olsson (1917) placed these beds in the lower part of the Yorktown Formation. The stage name "Murfreesboro" is invalid, however, because of prior usage.

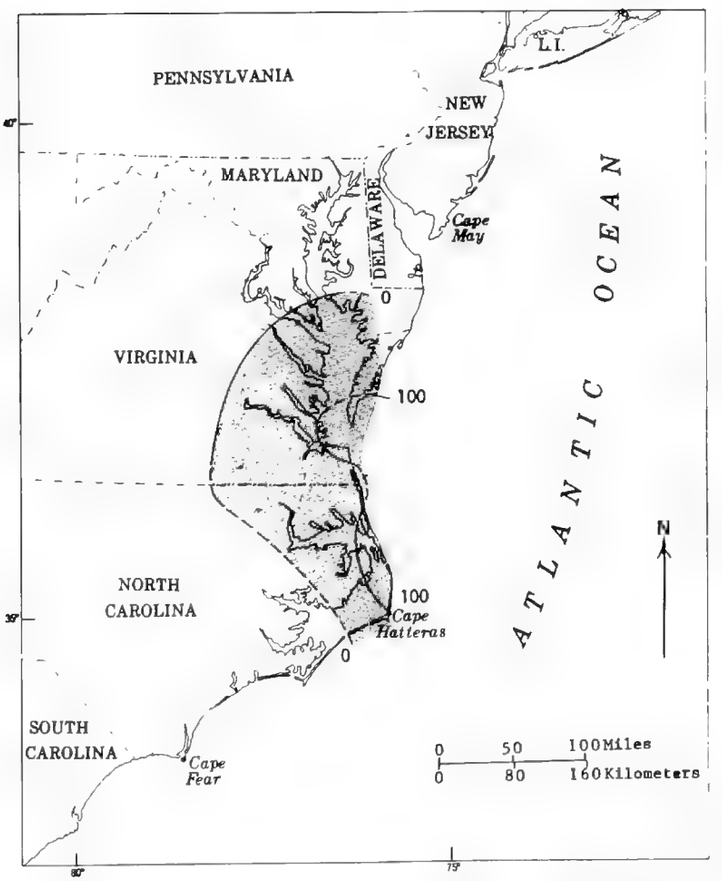


FIGURE 31.—Isopachous map of the "Virginia St. Marys" beds (upper Miocene). Contours are in feet and are indicated by dashed lines where locations are approximate.

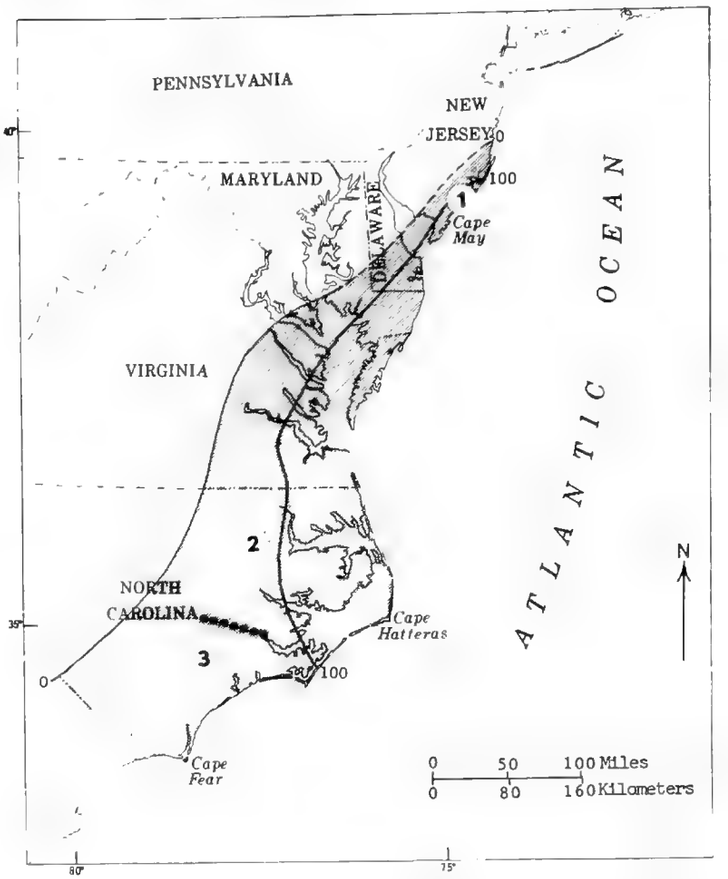


FIGURE 32.—Isopachous map of the Yorktown Formation and equivalent strata (contours are in feet): 1 = Cohansey Sand, 2 = Yorktown Formation and "Virginia St. Marys" beds, 3 = Duplin Formation. Formational limits are dashed where approximately located. The dotted line is the approximate location of the change between the latter two formations (modified from Gibson, 1970).

The "Virginia St. Marys" beds are grayish blue to greenish blue clayey sand and sandy clay, commonly very shelly. The beds are 25 to 75 feet (7.6–23 m) thick in the outcrop belt in Virginia and thicken down-dip to more than 200 feet (61 m) in the Norfolk Moores Bridge Well. They generally sit upon the Calvert Formation in the Salisbury embayment in Virginia. In North Carolina, the "Virginia St. Marys" beds crop out near Murfreesboro (Figure 4: loc. 28). Strata to the east and southeast of Murfreesboro in the subsurface are placed in this unit. They contain a distinctly different foraminiferal assemblage, reflecting a deeper water environment, which is difficult to correlate with the microfaunas of outcrop sections.

The exact time of the "Virginia St. Marys" beds is uncertain because of the absence of diagnostic planktonic foraminifers in outcrop samples. In addition to the late Miocene age for the underlying St. Marys Formation, a late Miocene age is suggested by K/Ar dates of 8.7±0.4 my and 6.46±0.15 my on "Virginia St. Marys" beds by Blackwelder and Ward (1976:5). The upper age limit of latest Miocene to earliest Pliocene is drawn from the planktonic foraminiferal placement of the lowermost part of the Yorktown Formation into zone N19 (see p.363) and by the K/Ar date of 4.4±0.2 my on lower beds of the Yorktown (Blackwelder and Ward, 1976:8). That considerable late Miocene time is represented by the "Virginia St. Marys" beds is documented by the presence of three consecutive pecten range zones in these strata (Gibson, in prep.) Hiatuses are not unexpected in strata of shallow-marine origin, and at least three are present in the "Virginia St. Marys" beds. This interpretation arises from the sudden appearance of three different chronologic subspecies of pectens above undulating surfaces accompanied by slight changes in the sediments. These zones and hiatuses are best exposed in the James River Valley from Cobham Bay westward to Petersburg.

Environment of Deposition.—Initial deposition in the new center of deposition of the Salisbury embayment constitutes the "Virginia St. Marys" beds. Deposition of the lower strata took place in shallow marine water of less than 30 meters as interpreted from the low species diversities of benthic Foraminifera (less than 15), the dominance of *Elphidium excavatum*, and the sparsity of planktonic foraminifers. The distribution of these strata in Virginia is limited to the eastern part of the embayment. Equivalent strata are not known in the Albemarle embayment, which suggests that no significant subsidence took place there.

Beds of the *Chesapecten middlesexensis middlesexensis* total range subzone overlie the initial deposits of the "Virginia St. Marys" beds and form much of the middle and upper parts of Mansfield's (1943) zone 2 of the St. Marys in Virginia. These strata still represent shallow-marine environments of less than 30 meters and contain foraminiferal assemblages similar to those of the underlying beds. It is thought that they accumulated during a transgression in the Salisbury embayment, because they are found beyond the known geographic extent of the initial strata of the "Virginia St. Marys" beds.

In the highest part of the "Virginia St. Marys" beds, the transgressive sea extended considerably westward, reaching Petersburg (Lieutenant Run, Figure 4: loc. 23) and northward to the Nomini Cliffs (Figure 4: loc. 18). Deposition took place in shallow open marine water of less than 30 meters; the benthic foraminiferal assemblages have species diversities of 10 to 20 with *Elphidium excavatum* dominant, and few planktonic foraminifers occur. These strata contain a transitional form of *Chesapecten middlesexensis–C. jeffersonius.* Significant downwarping of the northern part of the Albemarle embayment began at this time because deposits of this age extend to the west of Halifax, North Carolina (Figure 4: loc. 29). Around Halifax, deposition occurred in shallow open marine water of 15 to 30 meters, marked again by the low species diversities of 12 to 20, few planktonic Foraminifera and dominance of *Elphidium excavatum.* To the east, near Murfreesboro, deeper water deposits are found; the species diversity of benthic Foraminifera increases to 45 and planktonic specimens increase to 5 to 8 percent. These beds accumulated in open marine water about 30

to 60 meters deep. According to Bailey (1973:53) these beds, which contained his assemblage I, formed in depths of 22 to 120 meters.

## Yorktown Formation

The Yorktown Formation and its laterally equivalent formations represent one of the two most widespread transgressions of the Neogene seas in the central Atlantic Coastal Plain, the other having occurred during deposition of the Calvert Formation and equivalents. The Yorktown Formation is probably the most widespread of the Neogene transgressive units in the central and south-central parts of the Atlantic Coastal Plain.

The distribution of the Yorktown Formation and equivalent strata is shown in Figure 32; the distribution of the subdivisions of the Yorktown is shown in Figures 33 through 35. The Yorktown

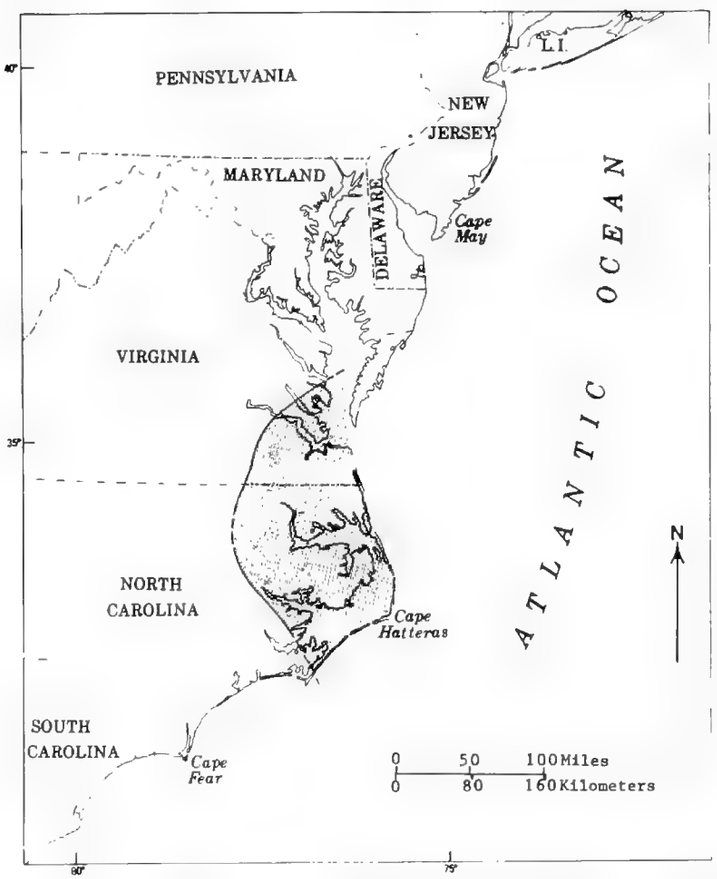


FIGURE 33.—Map of the distribution of the lower Pliocene zone 1 or *Placopecten clintonius* zone of the Yorktown Formation of Mansfield (1943). Limit of zone is indicated by a dashed line where approximately located.

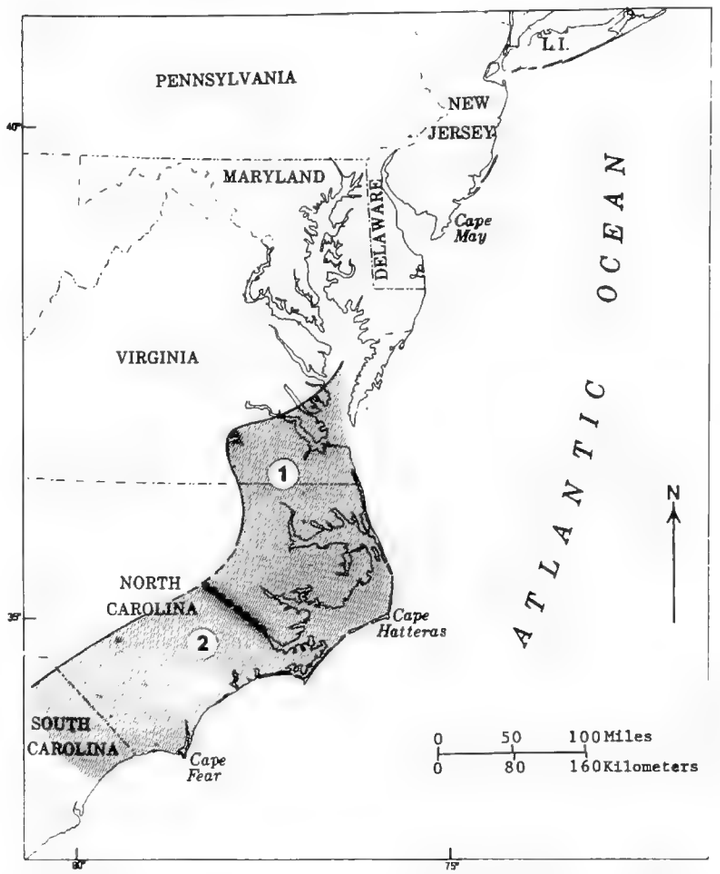


FIGURE 34.—Map of the maximum distribution of the lower and middle parts of zone 2 of the Yorktown Formation of Mansfield (1943) and equivalent strata (lower and upper? Pliocene). 1 = Manfield's Yorktown Formation, 2 = Duplin Formation; dotted line is the approximate location of change between formations.

reaches thicknesses of greater than 300 feet (91 m) near Norfolk, Virginia, and probably also beneath the outer banks of North Carolina.

The lithology of the Yorktown Formation is variable because the wide geographic distribution reflects a number of environments. Clastic units dominate northern Virginia and southern North Carolina, and indicate that the Piedmont uplift had proceeded southward by this time. Bluish clayey sand is dominant; bluish sandy clay is secondary; molluscan shells are common in most strata. The weathered deposits, particularly the sandier, more permeable, units are buff to yellow. Beds of shell hash, in which broken shells compose well over 50 percent of the sediment, are common and many are crossbedded, representing offshore bars and associated environments. Because these

strata are very permeable, most are highly oxidized and some are indurated.

The distribution of the Yorktown Formation continued the significant change in depositional pattern seen in the underlying "Virginia St. Marys" beds. The locus of deposition shifted southward from southern Maryland to southern Virginia as the western shore of Maryland was uplifted. This trend toward a more southerly center of deposition began in the "Virginia St. Marys" beds and continued upward through the formation until southern Virginia (including the Norfolk arch) and northern and central North Carolina were covered by the Yorktown sea. The latest "Yorktown Formation" transgression and its equivalents (Waccamaw and Croatan formations) accumulated in a more restricted area covering only the southeastern part of Virginia and eastern North Carolina. The northern part of the central Coastal Plain from Maryland to southern Virginia was then a positive area.

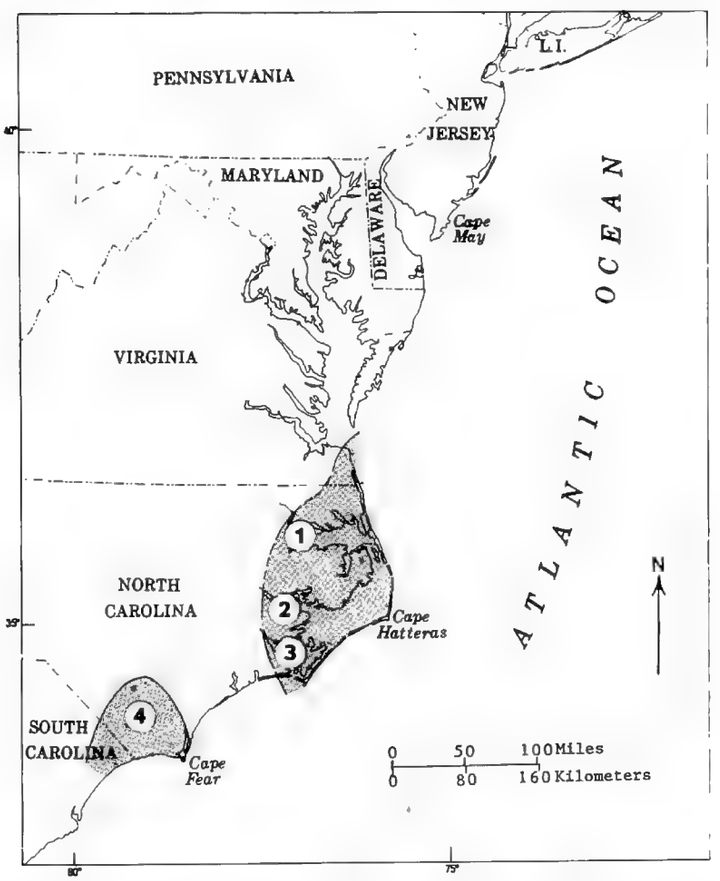


FIGURE 35.—Map of the distribution of the upper Pliocene and lower Pleistocene strata. Limit of strata is indicated by a dashed line where approximately located. 1 = "Yorktown" Formation, 2 = Croatan Formation, 3 = James City Formation of DuBar and Solliday (1963) (=Croatan), 4= Waccamaw Formation.

| VIRGINIA | | | NORTH CAROLINA | |
|---|---|---|---|---|
| YORKTOWN FORMATION | Zone 2 | Beds at Suffolk, with bed at Biggs Farm at top | Uppermost Yorktown with bed at Mt. Gould at top | Duplin marl |
| | | Beds at Yorktown | Equivalent to the beds at Yorktown, Va | |
| | | Chama-bearing bed | Chama-bearing bed | |
| | Zone 1 | | Zone 1 | |
| ST. MARYS FORMATION | Zone 2 | | ST. MARYS FORMATION (?) | |
| | Zone 1 | | (?) | |

FIGURE 36.—Correlation chart of the Yorktown and St. Marys formations according to Mansfield (1943).

The changes in distribution reflect upwarp in the central and northern Salisbury embayment in Maryland and northern Virginia and significant downwarping in southern Virginia and the Albemarle embayment in North Carolina.

The present definition of the Yorktown Formation does not imply continuity of deposition in all outcrop sections. The Yorktown Formation as used herein accumulated during early Pliocene through late Pliocene(?) time (Hazel, 1977; see also p.363). Faunal changes and lithologic discontinuities are present in the Yorktown Formation as documented by Gibson (1967) and Hazel (1977), and herein illustrated in Figures 24 and 26.

Mansfield (1943) divided the Yorktown Formation in Virginia into two faunal zones, the lower, zone 1, called the *Pecten clintonius* zone, and the upper, zone 2, called the *Turritella alticostata* zone. Zone 2 was divided into three units, in ascending order, the *Chama*-bearing bed, the beds at Yorktown, and the beds at Suffolk (Figure 36).

At the top of the Suffolk unit, he placed the bed at Biggs Farm (exposure not located by later workers), which he considered to be the youngest part of the Yorktown in Virginia.

Blackwelder and Ward (1976) proposed four member names for the Yorktown Formation in Virginia that encompass Mansfield's zone 1 and much of his zone 2. These four members are recognizable in the areas of the James and York rivers. Johnson (1969:10) proposed that some of the lithologically distinct beds or members of the Yorktown along the James and York rivers are lateral facies, but biostratigraphic correlation based on the pectens (Gibson, in prep.) supports Mansfield's (1943) view of a vertical succession of these beds.

Mansfield (1943) studied the Yorktown strata in North Carolina and compared them with the Virginia succession. The youngest part of the Yorktown in North Carolina recognized by Mansfield was at Mt. Gould Landing along the Chowan River. Mansfield (1943:12) concluded that the strata were younger than any Yorktown in Virginia. This conclusion is supported by Hazel (1977) on the basis of ostracodes and by Gibson (in prep.) on the basis of pectens. Gibson (1962) correlated the beds along the Chowan River with the Waccamaw Formation in southern North Carolina on the basis of benthic Foraminifera; this correlation is supported by Hazel (1977) and Gibson (p.364). These beds are further correlated with the Croatan Formation as used in the Lee Creek Mine and other places in east-central North Carolina on the basis of the ostracodes (Hazel, 1977), foraminifers (see p.364), and pectens (Gibson, in prep.).

Hazel (1977) found strata at Yadkin, Virginia, which he considered younger than any other strata in the Yorktown Formation in Virginia, and probably equal in age to the upper beds along the Chowan River. Strata containing benthic Foraminifera characteristic of latest Yorktown age also occur in the upper part of the Moores Bridge Well at Norfolk (Figure 4: loc. 25) at depths from about 90 to 115 feet (27 to 35 m). These strata are likely equivalents of the Yadkin deposits, and both may be the same age as those originally reported by Mansfield (1943) at Biggs Farm.

Beds equivalent to zone 1 of Mansfield's Yorktown, characterized by the presence of *Placopecten clintonius*, crop out only near Murfreesboro in North Carolina (Figure 4: loc. 28), but they are present in the subsurface southward to the Lee Creek Mine (Figures 23, 24, 27); they also extend to the east (Figure 33). Strata equivalent to zone 2 of Mansfield's zonation extend southward in North Carolina to New Bern (Figures 4: loc. 34; and 34).

South of central North Carolina, strata of Yorktown age are placed in the Duplin Formation (Mansfield, 1943).The historic basis for separating Duplin from Yorktown is the warmer water fauna of the Duplin rather than any striking lithologic change (Mansfield, 1943). According to Mansfield (1943:13), the Duplin Formation represents only the younger part of his zone 2 of the Yorktown. The diagnostic species of Duplin pectens and benthic foraminifers confirm its middle and late Yorktown age (see p.363). However, the youngest parts of the Yorktown Formation as exposed along the Chowan River in North Carolina are younger than the Duplin Formation.

In the Salisbury embayment, more than 200 feet (61 m) of Yorktown strata are present in wells in the southern part of the Delmarva Peninsula (Accomack Well, Virginia; Figure 4: loc. 20). Farther north on the Delmarva Peninsula, Anderson (1948:19) provisionally placed 200 feet (61 m) of sand and gravel described from the Hammond Well into a nonmarine facies of the Yorktown Formation. No biostratigraphic data are available to confirm this, however.

Richards and Harbison (1942) correlated part of the Cohansey Sand in New Jersey with the Yorktown Formation. The Cohansey is composed of coarse quartz sand and beds of clay and gravel. It contains few fossils, but has been tentatively correlated with the Yorktown. Isphording and Lodding (1969) considered the Cohansey to have accumulated in a regressive phase of late Miocene deposition, essentially a continuation of Calvert and Choptank deposition. This would place the lower part of the Cohansey in the middle Mio-

cene, leaving its youngest beds undated. The presence of shallow-water strata of Miocene age offshore in the Cost B-2 Well (Smith et al. 1976:50) indicates that the Cohansey could be a regressive facies of any or all of the middle Miocene through Pliocene onshore units.

Environment of Deposition.—The Albemarle and Salisbury embayments contained open marine, inner- to middle-shelf environments followed by regressive marginal-marine environments during deposition of the lower and middle parts of the Yorktown Formation and equivalents. The greatest water depths postulated for these strata are 80 to 100 meters (Gibson, 1967:645) and are based on foraminifers. Bailey (1973:53–58) assigned similar depths (maximum of 120 m) to two intervals on the basis of mollusks. In general, the Yorktown Formation in the Albemarle embayment includes older strata deposited in deeper water than those deposited in the southern part of the Salisbury embayment.

The *Placopecten clintonius* zone (zone 1 of Mansfield's Yorktown Formation) is one of the most widespread units in the Yorktown Formation. This zone extends from east-central Virginia southward across the Norfolk arch into the Albemarle embayment and reaches southward almost to New Bern (Figures 4: loc. 34; and 33). The depositional depths of 80 to 100 meters in the Lee Creek Mine (Gibson, 1967), suggest that the zone originally was even more widespread, but has been partly removed by erosion. The *P. clintonius* zone is the oldest post-Pungo River deposit in the southern part of the Albemarle embayment and is the initial deposit of the Yorktown Formation in the Lee Creek Mine. This indicates that downwarping occurred here later than in the northern part. The lower several feet of this zone are rich in dark brown to black phosphatic nodules as large as 1 foot (30 cm) in diameter. These nodules are reworked by physical and chemical processes from the phosphatic sand of the Pungo River Formation. They formed in continental, marginal-marine, and marine environments in post-Pungo River time and were incorporated into the basal strata of the Yorktown Formation. Numerous vertebrate fossils, including bones of whales, porpoises, and seals, and shark teeth are included in this basal transgressive unit. Molluscan shells, particularly *Placopecten clintonius*, are abundant (Figures 26, 27). These figures also show the burrowed surface at the top of the Pungo River Formation and the reworked phosphatic nodules. The *Placopecten clintonius* zone, along with the underlying highest part of the "Virginia St. Marys" beds, represent the deepest water deposition of any outcropping Yorktown strata in North Carolina. The depositional depths for this zone in Virginia were not as great as in the Lee Creek Mine; most were 30 meters or less, as indicated by lower foraminiferal species diversity and fewer planktonic foraminifers (Gibson and Buzas, 1973:231).

The Yorktown strata above the *Placopecten clintonius* zone in central and northern North Carolina are part of a regressional sequence as shown in the Lee Creek Mine by Gibson (1967) and in northeastern North Carolina by Hazel (1971), Bailey (1973), and Gibson (unpub. data). In the Lee Creek Mine, middle beds of the Yorktown accumulated in water of 30 meters or less. In northern North Carolina, strata containing diverse foraminiferal and molluscan assemblages and common planktonic Foraminifera (*Placopecten clintonius* zone) grade upward into beds containing molluscan assemblages almost exclusively composed of *Mulinia congesta* and low-diversity foraminiferal assemblages dominated by *Elphidium excavatum* (Mansfield's zone 2) with no planktonic specimens. *Elphidium excavatum* also is characteristic of shallow-marine, lagoon, and sound environments. These assemblages are associated with laminated clay beds near Murfreesboro and Palmyra, North Carolina (Figure 4: locs. 28, 30), which suggest deposition in a lagoon or sound.

The regression or subsequent erosion probably caused the missing section in the upper part of Mansfield's zone 2 of the Yorktown in the Lee Creek Mine (Gibson, 1967, Hazel, 1977). Other Yorktown erosional surfaces, such as the one separating units 2 and 3 in the Lee Creek Mine (Figure 24), are present throughout Virginia and North Carolina. Whether these are submarine or subaerial scour surfaces is not known at present.

Generally, the environments as interpreted from foraminiferal assemblages show little change. In many sections, the molluscan assemblages, particularly the pectens, do change across the scour surfaces and suggest that some time is missing. These scour surfaces help in defining members of the Yorktown Formation in Virginia.

The initial deposition of the lower strata of the Yorktown occurred in shallower water than in the southern part of the Salisbury embayment in Virginia. The beds of the *Placopecten clintonius* zone were deposited in open marine water of less than 30 meters, and these depths were maintained during accumulation of much of the overlying Yorktown strata. The upper beds at Yorktown (zone 2 of Mansfield) contain high-angle, large-set crossbeds of medium to coarse sand and abundant shell hash. These are characteristic of barrier bars (Johnson, 1969:12, 24) and reflect a regression of the Yorktown sea in the Salisbury embayment. Beds belonging to zone 2 of Mansfield extend westward to Petersburg where they lie upon the uppermost part of the "Virginia St. Marys" beds (Figure 34). The upper beds at Petersburg are blue clay units, some containing bands of *Mulinia congesta* and foraminiferal assemblages dominated by 70 percent *Elphidium excavatum*. These upper beds probably were deposited in the lagoon or sound behind the barrier-bar sequence forming to the east.

This regression marked the end of Yorktown deposition in much of the Salisbury embayment in Virginia. In the southeastern part, however, a later transgression deposited upper Pliocene to lower Pleistocene strata seen at Yadkin (Hazel, 1977) and at Norfolk (Moores Bridge Well, see p. 74). This latest "Yorktown Formation" transgression covered much of the eastern part of the Albemarle embayment as seen in deposits along the Chowan River, at Terra Ceia, in the upper beds in the Lee Creek Mine, and near James City along the Neuse River (Figures 4: loc. 35; and 35). The beds along the Chowan River were placed in the Yorktown Formation by Mansfield (1943) and are provisionally referred there by Hazel (1977) and Gibson (see p.364). In the southern part of the Albemarle embayment these strata are placed in the Croatan Formation (Hazel, 1977). These beds also indicate a regressional sequence toward the top. In the Lee Creek Mine, the lower strata of the Croatan were deposited in an open marine environment about 30 meters deep; later beds were deposited in open marine water of less than 15 meters depth; uppermost beds accumulated in marginal-marine environments (Gibson, 1967). Bailey (1973) concluded that equivalent beds along the Chowan River accumulated initially in a shallow sublittoral environment, becoming even shallower estuarine, sound, lagoon, and inlet environments when the upper parts were deposited. Thus, at the end of the latest "Yorktown Formation" depositional cycle, a series of marginal-marine, sound, lagoon, and other estuarine environments was found from the Chowan River southward through the Lee Creek area to the Neuse River. Howard (1974) believed that the Croatan Formation near James City on the Neuse River (= James City Formation of DuBar and Solliday (1963); Hazel, 1977) formed in a shallow bay or sound; this would extend the marginal-marine belt to James City (Figures 4: loc. 35; and 35).

The crest of the Norfolk arch was covered mostly by marginal-marine deposition during Yorktown time. Occasionally, shallow-marine deposition occurred on part of much of the arch, particularly during deposition of zone 1 of the Yorktown (Clark and Miller, 1912:159). Wells on top of the arch (Figure 37) penetrate thick sequences of fine-grained sediments, primarily clay, largely devoid of megafossils, but with foraminiferal assemblages dominated by *Elphidium excavatum*. The precise age of these strata is uncertain at this time because of the limited faunas.

Erosion and/or nonmarine deposition took place in the northern and western parts of the Salisbury embayment during Yorktown time. In the northeast part of the embayment, coarse clastic deposits still were originating in the uplifted Appalachians as seen in the coarse clastic sequence of the Hammond Well and at Accomack on the Eastern Shore (Figure 4: locs. 13, 20). The

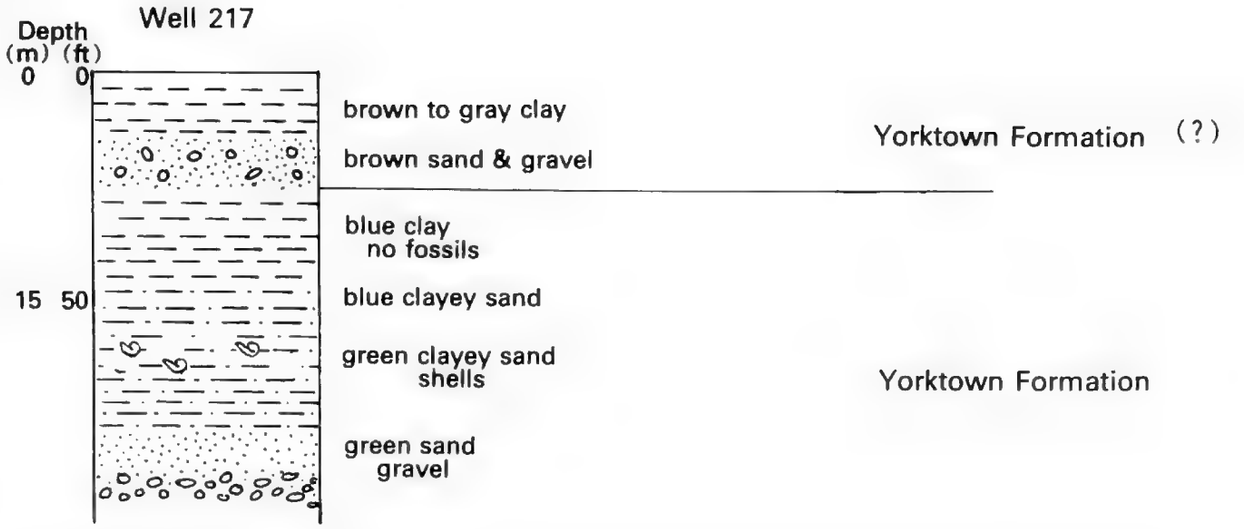


FIGURE 37.—Geologic column for Well 217, near New Bohemia, Prince George County, Virginia, showing small amount of open marine sediments in section in Yorktown Formation.

uplift of the northern source areas had moved southward by Yorktown time to include the adjacent Piedmont in Virginia and North Carolina, which supplied clastic sediments to the southern Salisbury and Albemarle embayments.

Farther south in North Carolina, the shallow environments persisted as seen in the Duplin Formation and younger part of the Waccamaw Formation. Strata of early Yorktown age are missing in this area. Copeland (1964:229) concluded that the Duplin Formation was deposited in depths of 30 to 60 feet (9 to 18 m). Howard (1974:129, 130) considered deposition to have been in water less than 37 meters deep and mostly less than 18. Gibson (unpub. data) found similar depths for many of the exposures. Additional evidence for near-shore deposition in southern North Carolina are the delta lobes, which DuBar et al. (1974:153, 171) attributed to the Duplin Formation.

The Waccamaw Formation was deposited on the Cape Fear arch in southern North Carolina during the later "Yorktown Formation" transgression. Deposition occurred in shallow open marine environments (Gibson, 1962:68). Howard (1974) recognized two environments in the Waccamaw in this area, one of shallow open marine (less than 15 m depth and high energy) and the second of lower salinity shallow bay. The shallowness of the Waccamaw environments to the south and the Croatan environments to the north suggests that the intervening area received no marine or marginal-marine deposition (Figure 35).

## Addendum

Since the original submission of this manuscript in 1978, new stratigraphic knowledge has led to several changes in the stratigraphic nomenclature used herein. Ward and Blackwelder (1980) gave the name Eastover Formation to the beds previously and herein termed the "Virginia St. Marys." Gibson (1982) demonstrated that an older cycle of sand and diatomaceous clay beds of the Calvert Formation, termed the Dunkirk beds, underlies the Popes Creek Sand Member along the Patuxent River.

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# Age and Correlation of the Yorktown (Pliocene) and Croatan (Pliocene and Pleistocene) Formations at the Lee Creek Mine

*Joseph E. Hazel*


## ABSTRACT

The fossiliferous beds above the Pungo River Formation (middle Miocene) in the Lee Creek open pit mine in Beaufort County, North Carolina, are approximately 70 feet (21.3 m) thick. This thickness includes 46 feet (14 m) that is correlative with the Yorktown Formation of the type area and is referred to that unit, and, above the Yorktown, a fossiliferous section 23 feet (7 m) thick that is assigned to the Croatan Formation.

The 149 species or subspecies of ostracodes identified were from 16 samples from the Yorktown and Croatan. Coefficients of faunal similarity were calculated for all samples, and the resulting matrix was subjected to unweighted pair-group cluster analysis. Three major faunal groupings were delineated. The principal faunal discontinuity occurs at the Yorktown-Croatan contact about 46 feet (14 m) above the base of the Yorktown. The beds below this level belong to the *Pterygocythereis inexpectata* and *Orionina vaughani* ostracode assemblage zones. Correlation with other Coastal Plain deposits containing planktonic foraminifers indicates that the *Orionina vaughani* assemblage zone is planktonic foraminifer zones N19 and N20 in age and that the *Pterygocythereis inexpectata* assemblage zone may approximate the lowest part of planktonic zone N19 in age. Thus, the Yorktown in the Lee Creek Mine is of early Pliocene age. This is seemingly corroborated by a K/Ar date of 4.4±0.2 my on the *Orionina vaughani* assemblage zone in Virginia.

A third major faunal assemblage is found in the beds of the Croatan Formation, which are referable to the *Puriana mesacostalis* ostracode assemblage zone. The upper part of the Croatan can be correlated with rocks in Florida and North Carolina that have been radiometrically dated by the He/U method at about 1.8 to 1.9 mya. A tentative He/U radiometric date of 2.4 mya was obtained for the lower part of the Croatan at the mine. If a date of about 2.0 mya is used for the Pliocene-Pleistocene boundary, the Croatan as used in the mine spans the Pliocene-Pleistocene boundary.


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## Introduction

Texasgulf's Lee Creek open pit phosphate mine is on the south bank of the Pamlico River in Beaufort County, North Carolina. The mine has been the subject of considerable interest since it opened in 1963, not only because of the importance of the primary phosphorite deposits but also because it affords access to an exposure of fossiliferous upper Cenozoic rocks more than 120 feet (36.6 m) thick, an uncommon phenomenon in the Coastal Plain.

This paper is concerned with the ostracodes and their biostratigraphy in the beds of the Yorktown and Croatan formations exposed in the mine walls. This section is interesting not only because of the excellent exposure, but because it is only about 25 miles (40.25 km) north of the Neuse River, the approximate southern limit of the region where the term "Yorktown" is com-

monly used, and it is in the only area where the term "Croatan" (=James City Formation of DuBar and Solliday, 1963) has been used. South of the Neuse, in the Carolinas and in Georgia, the terms "Duplin" and "Waccamaw" are generally used for rocks considered to be at least in part equivalent to the Yorktown and Croatan. The Duplin is known to contain a warmer water fauna than the Yorktown (for example, Mansfield, 1929); thus, there is also a biogeographic boundary in the vicinity of the Neuse River, although at present this boundary is poorly understood.

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## Previous Work

Gibson (1967) made the first study of the fossiliferous rocks in the Lee Creek Mine, assigning them to the Pungo River and Yorktown formations. He measured a 66.4-foot (20.2 m) section of Yorktown in the test pit, in the northeast part of the mine area as shown in Figure 1. Gibson assigned the Yorktown in the mine to the later Miocene, because he concluded that the lowermost beds contained a planktonic foraminifer assemblage consistent with that age. Gibson (1967:638) also pointed out that the presence of

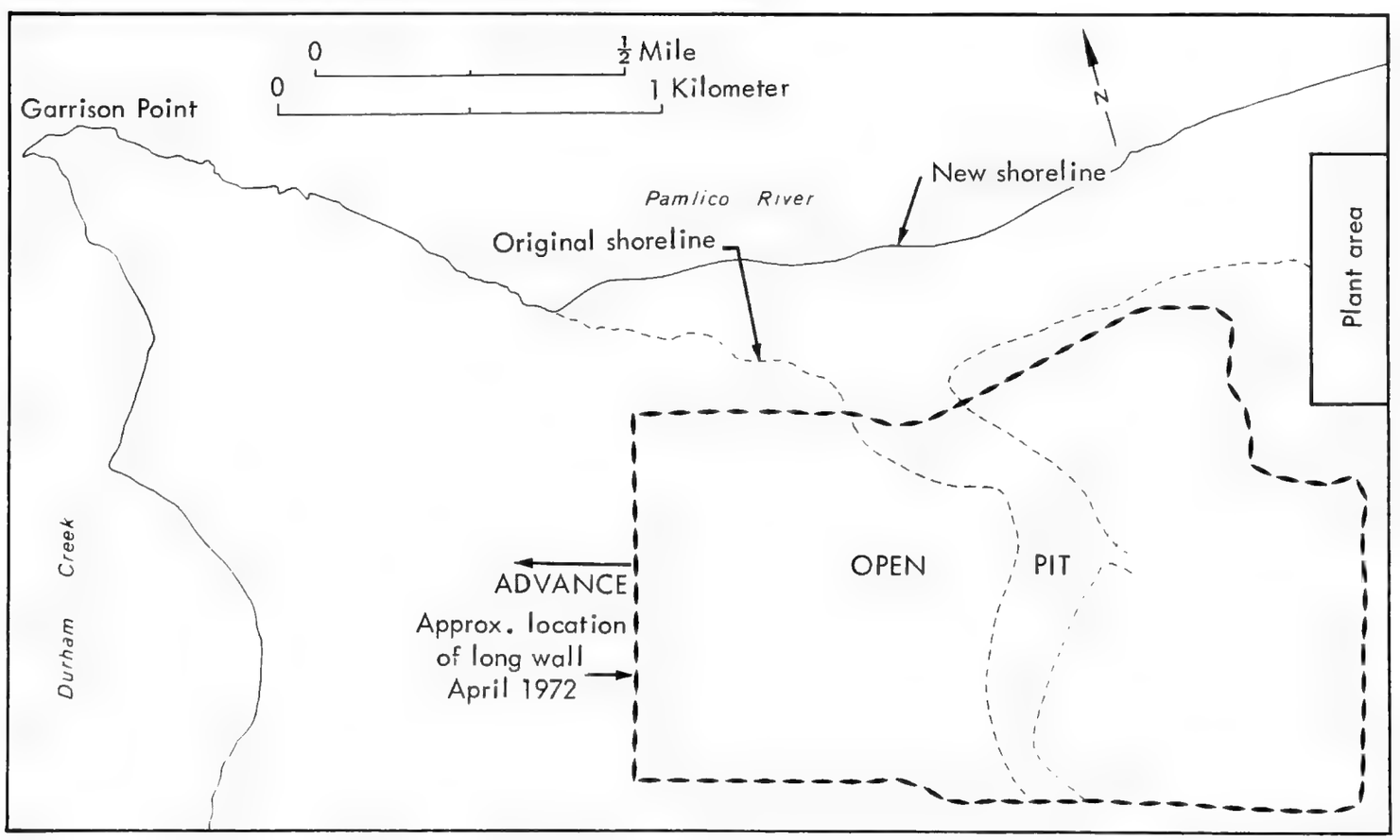


FIGURE 1.—Location of the Texasgulf Inc. Lee Creek open pit phosphate mine near Aurora, North Carolina. The samples used in the present study were taken from the southwestern part of the mine.

*Placopecten clintonius* (Say) in the lowermost beds indicates correlation with Mansfield's (1929, 1943) *Placopecten clintonius* zone (zone 1) of the Yorktown, and that the presence of *Ostrea sculpturata* in the middle part of the section suggests placement in the lower part of Mansfield's *Turritella alticostata* zone (zone 2). On the basis of foraminifer assemblages, Gibson (1967:647) concluded that the Yorktown in the mine was deposited initially in cool-temperate waters nearly 100 m deep and finally in warmer waters less than 15 m deep.

In 1969, Hazel (1971a:10) referred a 69-foot (21.0 m) section in the southwestern part of the mine to the Yorktown. On the basis of a cluster analysis of 43 Yorktown collections (10 from the Lee Creek Mine), he concluded that the lower few feet of the Yorktown in the mine belonged to the *Pterygocythereis inexpectata* ostracode assemblage zone, and approximately the upper 12 feet (3.7 m) to the *Puriana mesacostalis* assemblage zone; the rest of the accessible section between these two zones was placed in the *Orionina vaughani* assemblage zone. Hazel (1971a:8) assigned the *Puriana mesacostalis* assemblage zone to the Pliocene and suggested that more of the Atlantic and Gulf Coastal Plain deposits traditionally assigned to the upper Miocene could be Pliocene. Hazel (1971b:373) concluded that the early Yorktown assemblage lived under mild or warm-temperate climatic conditions, that warm-temperate conditions prevailed during most of Yorktown time, and that a subtropical marine climate was present in Croatan (his late Yorktown) time.

Swain (1974) studied ostracodes from the Yorktown Formation from various localities in Virginia and North Carolina. Most of the specimens studied by Swain were picked from carbon tetrachloride floats prepared for the study of foraminifers by T.G. Gibson of the U.S. Geological Survey. Few species and specimens were available for study, as Swain indicated in his descriptive section, probably because ostracodes (particularly single valves) do not "float" well. Yorktown samples, 500 to 1000 $cm^3$ in size, when picked after only washing or after concentrating the carbonate fraction by using a soap float technique (Howe, 1941; Gibson and Walker, 1967), have yielded hundreds and on occasion thousands of ostracode specimens (this study and Hazel, 1971a). Swain (1974), therefore, would have had difficulty in recognizing the assemblage zones established by Hazel (1971a) because he studied only a small number of ostracode specimens. Swain's (1974) study was further impeded when he tried to use the particular species for which Hazel's (1971a) assemblage zones were named as index or guide fossils, despite the fact that Hazel clearly stated that the zones were assemblage zones.

Swain (1974:10) also studied some samples from the Lee Creek Mine and is of the opinion that the large assemblages reported by Hazel (1971a) from the lower part of the Yorktown at the mine are in part reworked from the underlying Miocene Pungo River Formation. The writer has processed several samples from the lower part of the Yorktown at the mine and has found no evidence of reworking of ostracodes from the Pungo River into the Yorktown. T.G. Gibson (pers. comm., 1975) has also studied many samples from the lower part of the Yorktown at the mine, and he, too, finds no evidence of reworking. The Pungo River carries a taxonomically distinct and differently preserved assemblage. Swain (1974:10) stated that these lower beds of the Yorktown in the mine are correlative with the middle or upper part of the Yorktown of the other sections he studied. The ostracodes (Hazel, 1971a, and p. 93 herein) and mollusks (Gibson, 1967:638) indicate an obvious correlation with the lower part of the Yorktown of the type area.

Most of Swain's samples (1974) were from his "lower Yorktown," and some of these at least are actually from the underlying Eastover Formation of Ward and Blackwelder (1980). Specifically, samples from Swain's lower part of the Yorktown at localities 5, 6, 7, 9, 10, and 11 may be partly or entirely from the Eastover Formation. The Eastover is late Miocene (Ward and Blackwelder, 1980:11) and (or) early Pliocene (Andrews, 1980:19) in age.

Swain (1974:9–11) considered the Yorktown Formation to be of late Miocene age; however, he presented no supporting evidence. He assigned

the beds at Colerain Landing and near Mt. Gould Landing on the Chowan River to the Pliocene(?). Hazel (1971a) assigned these localities to the Pliocene and placed them in the *Puriana mesacostalis* assemblage zone. Swain's (1974:11) argument that *Puriana mesacostalis* cannot be used as a guide for the Pliocene because it "was described from the upper Miocene Duplin Marl" is circular. There is no evidence that the Duplin is Miocene, but there is considerable evidence that it is Pliocene.

### Yorktown Formation

The Yorktown Formation is poorly understood as a lithostratigraphic unit, because the generally recognized Yorktown sediments contain a variety of lithologies. No extensive petrological examinations have been made of the Yorktown, and no extensive detailed mapping has been done at the surface or in the shallow subsurface over any sizable area where the term has been used. Without such a solid physical stratigraphic framework then, it is understandable, if not excusable, that the term "Yorktown" connotes a biostratigraphic, rather than lithostratigraphic, unit to many workers.

In the type area of the Yorktown, which can be defined as the valleys of the York and James rivers and the included peninsula, the Yorktown has generally come to mean the beds containing mollusks referable to Mansfield's (1929, 1943) *Placopecten clintonius* and *Turritella alticostata* zones (the so-called zones 1 and 2, respectively). These two zones are in need of redefinition and revision in the light of modern biostratigraphic thought; nonetheless, the Yorktown has been recognized in an area of about 17,000 square miles (44,030 square kilometers) as a unit of perhaps substage magnitude.

An "ian" ending was added to the Yorktown by Malkin (1953:767), who considered it a substage of the upper Miocene. She did not, however, study much of the Yorktown or discuss the distribution and correlation of this "substage" in any detail. Such nomenclatorial procedures have been followed before (for example, Murray, 1961). However, addition of "ian" endings to ostensibly lithostratigraphic terms in order to make their biostratigraphic use legitimate, although not necessarily confusing, is cumbersome and nomenclatorially undesirable; therefore, it is not followed here.

In North Carolina, rocks younger than the Yorktown of the type area have been included in the Yorktown by Clark et al. (1912), Mansfield (1943), MacNeil (1938), Hazel (1971a), and at the Lee Creek Mine by Gibson (1967) and Hazel (1971a). Gibson (1970) and Swain (1974) have also placed deposits demonstrably older than the classic Yorktown in the Yorktown Formation.

Lithologic units 1–4 of Figure 2 are correlative with the Yorktown Formation of the type area, and their lithologies do not differ from those of beds assigned to the Yorktown in northern North Carolina and Virginia. Therefore, units 1–4 (equivalent to units 1–5 of Gibson, 1967) are assigned to the Yorktown Formation.

### Croatan Formation

Units 5–7 (equivalent to Gibson's, 1967, units 6–9) in the mine have been referred to the James City Formation of DuBar and Solliday (1963) by DuBar, Solliday, and Howard (1974:109). The James City was proposed as a substitute for the Croatan Formation of Dall (1892) by DuBar and Solliday (1963:215, 228), because Dall did not adequately define the Croatan Formation in his original work. Dall's collections apparently contained both Pliocene and Pleistocene species, and he did not designate a type section. Mansfield (1928:135) reviewed the situation and restricted the name Croatan "to those beds on or near the Neuse River which are of Pliocene age." According to DuBar and Solliday (1963:223) and DuBar, Solliday, and Howard (1974:106), however, the beds to which Mansfield restricted the name probably represent a Pleistocene unit containing reworked Pliocene fossils.

DuBar and Solliday (1963:228) selected as the type locality of their James City Formation the

outcrops on the Neuse River just below the town of James City, which is about 12 miles (19.2 km) from the town of Croatan. Mansfield (1936) had previously included these outcrops in the Croatan but did not tie the name to a type section. However, MacNeil (1938:19) did suggest this locality as the type section for the Croatan. Because this is in the area of the Croatan people (the unit was not named for the town) and MacNeil has indicated a type section, the writer sees no reason not to adhere to the rules of priority and retain the term "Croatan," suppressing the term James City. Attention is called, however, to the clarifying efforts of DuBar and Solliday (1963) and particularly DuBar, Solliday, and Howard (1974).

Dall used the term "Croatan beds," and Mansfield referred to the "Croatan Sand," even though several lithologies are present in the Croatan (see DuBar, Solliday, and Howard, 1974). The writer believes that the unit should be referred to as the Croatan Formation.

## Collections and Analyses

The Lee Creek Mine was visited again by the writer in April 1971, and a 69-foot (21.0-m) section of Yorktown was measured in the southwest area of the mine. Collections were made from most of the beds that were inaccessible in the middle part of the formation in 1969 (Hazel, 1971a:10). These and the original collections were supplemented by collections made by L.W. Ward of the U.S. Geological Survey in 1972. The stratigraphic position of the various collections is indicated in Figure 2.

The 149 species or subspecies of ostracodes occurred in the 16 samples used for multivariate analysis. Three Yorktown samples, one from the Croatan, and two from unit 8, which may represent the Flanner Beach Formation (Pleistocene), were barren of ostracodes and are indicated by X in Figure 2. The samples were compared in Q-mode (samples compared on the basis of species content) by calculating Otsuka similarity coefficients between all samples and performing an unweighted pair-group cluster analysis (UPGM) on the resulting matrix. These techniques, as applied to biostratigraphy, have been described by Hazel (1970, 1971a). To minimize environmental or preservational differences between samples, the range-through method of calculation was used (see Cheetham and Deboo, 1963); that is, a species was counted as present in a sample for the purposes of the calculation of the similarity coefficient if it occurred in samples on either side of but not in the sample in question. The Q-mode dendrogram resulting from the cluster analysis is also illustrated in Figure 2.

In order to ascertain which species were primarily responsible for the groupings seen in Q-mode, an R-mode analysis (taxa compared with each other on the basis of the samples in which they occur) using the Otsuka coefficient was performed on all those species or subspecies that occur in more than one sample but not in all samples (a total of 85 taxa). The results of this R-mode analysis are presented in Figure 3.

## Alphabetical List of Species

The 149 ostracode species found in the Yorktown Formation at the Lee Creek Mine are listed alphabetically. The number to the left of the name is the computer code number assigned to the species. The numbers to the right of the name indicate occurrences in the samples of Figure 2. The plates and figures illustrating the species are also indicated.

| Code | Species | Sample | Illustration |
|---|---|---|---|
| 238 | *Actinocythereis captionis* | 2, 10–16 | Pl. 8: figs. 1, 2, 4 |
| 241 | *A. dawsoni* | 1, 3, 5–7, 9 | Pl. 9: fig. 1 |

| Code | Species | Sample | Illustration |
|---|---|---|---|
| 239 | *A. marylandica* | 1, 5, 6, 9 | Pl. 8: fig. 3 |
| 240 | *A. mundorffi*, small form | 2, 3, 5–8, 16 | Pl. 9: fig. 2 |
| 243 | *Acuticythereis laevissima* | 7, 8 | |
| 318 | *Anchistrocheles* sp. C | 11 | |
| 9 | *Aurila laevicula* | 6, 8 | Pl. 15: fig. 4 |
| 14 | *Bairdoppilata triangulata* | 1, 6, 8–16 | |
| 27 | *Bensonocythere blackwelderi* | 1, 6, 8, 9, 11–13 | Pl. 35: figs. 1, 2, 4; Pl. 37: fig. 4 |
| 32 | *B. bradyi* | 11 | Pl. 34: figs. 1, 2; Pl. 38: figs. 2, 4 |
| 24 | *B. calverti* | 1 | Pl. 34: fig. 5 |
| 19 | *B. gouldensis* | 4, 8, 9, 11, 15 | Pl. 34: figs. 3, 4; Pl. 37: figs. 2, 3 |
| 30 | *B. ricespitensis* | 12, 14 | Pl. 33: figs. 1–4 |
| 25 | *B. rugosa* | 3, 8, 10 | Pl. 32: figs. 3, 4; Pl. 37: fig. 1 |
| 21 | *B. trapezoidalis* | 1, 5, 9 | Pl. 32: figs. 1, 2 |
| 18 | *B. whitei* | 10–16 | Pl. 35: fig. 3 |
| 33 | *Bensonocythere* sp. M | 15 | |
| 319 | *Bensonocythere* sp. OO | 11 | |
| 320 | *Bensonocythere* sp. PP | 10, 13 | |
| 329 | *Bensonocythere* sp. QQ | 10 | |
| 330 | *Bensonocythere* sp. RR | 13 | |
| 44 | *Bythocythere* sp. B | 14 | |
| 47 | *Campylocythere laeva* | 5, 6, 9–16 | |
| 55 | *Caudites paraasymmetricus* | 13–15 | Pl. 12: figs. 2–4 |
| 56 | *Cnestocythere?* sp. | 16 | |
| 217 | *Cushmanidea* cf. *C. seminuda* | 14 | |
| 57 | *Cyprideis* sp. B | 15, 16 | |
| 62 | *Cytherella* sp. A | 5, 12 | |
| 321 | *Cytherella* sp. B | 1 | |
| 63 | *Cytherelloidea* sp. A | 14, 16 | |
| 106 | *Cytheridea campwallacensis* | 1, 4, 6 | Pl. 1: fig. 4; Pl. 2: figs. 1, 3, 4 |
| 111 | *C. carolinensis* | 10–15 | Pl. 3 |
| 107 | *C. virginiensis* | 2, 3, 5–15 | Pl. 1: fig. 3; Pl. 2: fig. 2 |
| 105 | *Cytheridea* aff. *C. virginiensis* | 3, 6, 7 | Pl. 1: figs. 1, 2 |
| 250 | *Cytheromorpha? curta* | 13 | |
| 68 | *C. incisa* | 9, 11, 13 | Pl. 21: figs. 1, 2; Pl. 23: figs. 5, 6 |
| 70 | *C. macroincisa* | 11, 15 | Pl. 22: figs. 1–5 |
| 67 | *C. suffolkensis* | 9, 11, 12 | Pl. 23: figs. 1–4 |
| 66 | *C. warneri* | 1, 5–10 | Pl. 22: fig. 6 |
| 322 | *Cytheromorpha* sp. I | 1 | |
| 71 | *Cytheropteron talquinensis* | 1, 2, 5–9, 12 | Pl. 9: fig. 4 |
| 72 | *C.? yorktownensis* | 1, 3, 5, 8–12, 14–16 | Pl. 9: fig. 3 |
| 317 | *Cytherura elongata* | 1, 3, 9, 15 | |
| 132 | *C. forulata* | 1, 5, 8, 9, 12–15 | |
| 75 | *C. howei* | 1, 5, 8, 12, 13, 15 | |
| 77 | *C. reticulata* | 9, 10, 13–15 | |
| 80 | *C. wardensis* | 6, 9, 15 | |
| 193 | *Cytherura* sp. | 5, 8 | |
| 323 | *Cytherura* sp. AA | 13, 15 | |
| 340 | *Cytherura* sp. BB | 13 | |
| 76 | *Cytherura* sp. D | 1, 3, 5, 7–9 | |
| 83 | *Cytherura* sp. L | 8–10, 14 | |
| 84 | *Cytherura* sp. M | 13, 15 | |
| 85 | *Cytherura* sp. N | 9, 12–16 | |
| 194 | *Cytherura* sp. U | 13 | |
| 316 | *Cytherura* sp. W | 13 | |

| Code | Species | Sample | Illustration |
|---|---|---|---|
| 90 | *Echinocythereis leecreekensis* | 10–12 | Pl. 36: figs. 1–3; Pl. 38: fig. 3 |
| 89 | *E. planibasalis* | 1, 5, 6, 8, 9 | Pl. 36: fig. 4 |
| 91 | *Eucythere declivis* | 1, 10, 12 | |
| 92 | *E. gibba* | 5, 6, 9, 11–13 | |
| 94 | *E. triangulata* | 11, 13 | |
| 96 | *Eucythere* sp. F | 5 | |
| 331 | *Hermanites ascitus* | 8, 9 | Pl. 11: figs. 1–3 |
| 115 | *Hirschmannia? hespera* | 10–12, 14 | Pl. 20: figs. 1, 2; Pl. 21: figs. 3, 4 |
| 114 | *H.? quadrata* | 10–14 | Pl. 20: figs. 3, 4 |
| 23 | *Hulingsina americana* | 2, 4, 6–14, 16 | |
| 156 | *H. glabra* | 10, 11, 13, 14 | |
| 22 | *H. rugipustulosa* | 1, 9–13, 15, 16 | |
| 128 | *Hulingsina* sp. C | 1, 9, 10, 12–15 | |
| 82 | *Hulingsina* sp. F | 11–15 | |
| 41 | *Hulingsina* sp. R | 5 | |
| 61 | *Hulingsina* sp. U | 7 | |
| 121 | *Leptocythere nikraveshae* | 14 | |
| 207 | *Leptocythere* sp. E | 13 | |
| 326 | *Leptocythere* sp. F | 11 | |
| 127 | *Loxoconcha edentonensis* | 12, 13 | Pl. 24: figs. 2, 4 |
| 136 | *L. matagordensis* | 13–16 | |
| 126 | *L. purisubrhomboidea* | 12 | |
| 131 | *L. reticularis* | 6, 8–10, 12, 13 | |
| 125 | *Loxoconcha* sp. C | 1–3, 5, 9 | |
| 130 | *Loxoconcha* sp. H | 3–7, 12–16 | |
| 133 | *Loxoconcha* sp. M | 5, 8, 9 | |
| 69 | *Loxoconcha* sp. S | 1 | |
| 216 | *Loxoconcha* sp. T | 14, 16 | |
| 13 | *Malzella conradi*, angulate form | 8–10 | Pl. 14: figs. 1, 2, 4 |
| 12 | *M. evexa* | 1, 3, 5, 6, 8–14, 16 | Pl. 14: fig. 3; Pl. 15: figs. 1–3, 5 |
| 139 | *Microcytherura choctawhatcheensis* | 1, 6–16 | Pl. 29: fig. 3 |
| 140 | *M. expanda* | 10, 11, 15, 16 | Pl. 30: figs. 1–3 |
| 149 | *M. minuta* | 3 | Pl. 31: figs. 1–3 |
| 138 | *M. similis* | 9–16 | Pl. 29: fig. 4; Pl. 30: fig. 4; Pl. 31: fig. 4 |
| 141 | *Microcytherura* sp. D | 13 | |
| 145 | *Microcytherura* sp. H | 1, 5, 8–10 | |
| 147 | *Microcytherura* sp. M | 12 | |
| 257 | *Microcytherura* sp. P | 15 | |
| 312 | *Microcytherura* sp. R | 10, 11, 15 | |
| 151 | *Muellerina bassiounii* | 10–13, 16 | Pl. 16: figs. 1, 4; Pl. 18: fig. 6 |
| 153 | *M. blowi* | 8–13 | Pl. 17: figs. 1, 3; Pl. 18: fig. 2 |
| 157 | *M. canadensis petersburgensis* | 1–3, 5–9 | Pl. 16: fig. 2; Pl. 18, figs. 1, 3 |
| 150 | *M. ohmerti* | 1, 3, 5, 7–16 | Pl. 16: fig. 3 |
| 152 | *M. wardi* | 1, 3, 9–14, 16 | Pl. 17: figs. 2, 4; Pl. 18: figs. 4, 5 |
| 160 | *Muellerina* sp. P | 4 | |
| 163 | *Murrayina barclayi* | 7, 9 | Pl. 11: fig. 4 |
| 162 | *M. macleani* | 1–5, 7 | Pl. 10: figs. 1–4 |
| 164 | *Murrayina* sp. E | 7 | |
| 309 | *Neocaudites angulatus* | 9, 15 | Pl. 6: figs. 2–4 |
| 328 | *N. subimpressus* | 8 | Pl. 5: fig. 4 |
| 166 | *N. triplistriatus* | 6, 8, 9 | Pl. 6: fig. 1 |
| 167 | *N. variabilus* | 11, 12 | Pl. 5: figs. 1–3; Pl. 7: fig. 1 |
| 172 | *Orionina vaughani* | 1, 5, 6, 8–16 | Pl. 12: fig. 1 |

| Code | Species | Sample | Illustration |
|---|---|---|---|
| 54 | *Palaciosa minuta* | 13 | Pl. 13: figs. 1, 3, 4 |
| 182 | *Paracyprideis* sp. C | 5–7, 9 | |
| 184 | *Paracypris* sp. B | 5 | |
| 189 | *Paracytheridea altila* | 1, 6, 9–16 | Pl. 28: fig. 4 |
| 188 | *P. cronini* | 5, 6, 8–10, 12, 13 | Pl. 28: figs. 1, 2; Pl. 29: fig. 1 |
| 223 | *P. mucra* | 13 | Pl. 29: fig. 2 |
| 190 | *P. rugosa* | 13, 15 | Pl. 28: fig. 3 |
| 327 | *Paracytheridea* sp. F | 9 | |
| 192 | *Paracytheroma stephensoni* | 13–15 | |
| 196 | *Paradoxostoma delicata* | 13, 15 | |
| 198 | *Paradoxostoma* sp. E | 11 | |
| 200 | *Paranesidea? laevicula* | 13 | |
| 201 | *Paranesidea* sp. B | 8 | |
| 98 | *Peratocytheridea bradyi* | 6, 7, 10–14, 16 | |
| 99 | *P. sandbergi* | 3–7, 9, 10, 12–16 | Pl. 4: figs. 1–3 |
| 324 | *P. setipunctata* | 15 | Pl. 4: fig. 4 |
| 104 | *Peratocytheridea* sp. J | 14 | |
| 143 | "*Pontocythere*" sp. I | 10, 13, 15, 16 | Pl. 38: fig. 1 |
| 230 | "*Pontocythere*" sp. G | 1, 3, 5–7 | |
| 155 | "*Pontocythere*" sp. J | 9, 13 | |
| 205 | *Propontocypris* sp. D | 3, 5, 7 | |
| 175 | *Proteoconcha gigantica* | 13 | |
| 173 | *P. jamesensis* | 9 | Pl. 25: figs. 1, 2; Pl. 27: fig. 2 |
| 178 | *P. mimica* | 9 | |
| 206 | *P. multipunctata*, sensu lato | 1, 5, 6, 8–15 | |
| 8 | *P. tuberculata* | 13 | |
| 177 | *Proteoconcha* sp. Z | 1 | |
| 215 | *Pseudocytheretta burnsi* | 1, 2, 4–11, 13–15 | Pl. 24: figs. 1, 3 |
| 224 | *Pterygocythereis inexpectata* | 1–7 | Pl. 7: fig. 3 |
| 227 | *Puriana carolinensis* | 1, 3, 6–16 | Pl. 27: figs. 1, 3, 4 |
| 228 | *P. convoluta* | 10, 13, 14 | Pl. 26: figs. 1, 2, 4 |
| 229 | *P. mesacostalis* | 13, 15 | Pl. 25: fig. 4 |
| 226 | *P. rugipunctata* | 6, 9, 12, 13 | Pl. 25: fig. 3; Pl. 26: fig. 3 |
| 165 | *Radimella confragosa* | 10–16 | Pl. 13: fig. 2 |
| 236 | *Sclerochilus* sp. B | 11, 14 | |
| 15 | *Thaerocythere carolinensis* | 12 | Pl. 19: figs. 1, 3, 4 |
| 78 | *T. schmidtae* | 10, 12, 14 | Pl. 19: fig. 2 |
| 16 | *Xestoleberis ventrostriata* | 10, 11, 13, 14 | |
| 169 | *Xestoleberis* sp. E | 12, 15 | |

## Numerical Computer Code List of Species

| Code | Species |
|---|---|
| 8 | *Proteoconcha tuberculata* (Puri, 1960) |
| 9 | *Aurila laevicula* (Edwards, 1944) |
| 12 | *Malzella evexa*, new species |
| 13 | *M. conradi* (Howe and McGuirt, 1935), angulate form |
| 14 | *Bairdoppilata triangulata* Edwards, 1944 |
| 15 | *Thaerocythere carolinensis*, new species |
| 16 | *Xestoleberis ventrostriata* Swain, 1951 |
| 18 | *Bensonocythere whitei* (Swain, 1951) |
| 19 | *B. gouldensis*, new species |
| 21 | *B. trapezoidalis* (Swain, 1974) |
| 22 | *Hulingsina rugipustulosa* (Edwards, 1944) |
| 23 | *H. americana* (Cushman, 1906) |
| 24 | *Bensonocythere calverti* (Ulrich and Bassler, 1904) |
| 25 | *B. rugosa*, new species |
| 27 | *B. blackwelderi*, new species |
| 30 | *B. ricespitensis*, new species |
| 32 | *B. bradyi*, new species |
| 33 | *Bensonocythere* sp. U |
| 41 | *Hulsingsina* sp. R |
| 44 | *Bythocythere* sp. B |
| 47 | *Campylocythere laeva* Edwards, 1944 |
| 54 | *Palaciosa minuta* (Edwards, 1944) |

| Code | Species |
|---|---|
| 55 | *Caudites paraasymmetricus*, new species |
| 56 | *Cnestocythere*? sp. |
| 57 | *Cyprideis* sp. B |
| 61 | *Hulingsina* sp. U |
| 62 | *Cytherella* sp. A |
| 63 | *Cytherelloidea* sp. A |
| 66 | *Cytheromorpha warneri* Howe and Spurgeon, 1935 |
| 67 | *Cytheromorpha suffolkensis*, new species |
| 68 | *Cytheromorpha incisa*, new species |
| 69 | *Loxoconcha* sp. S |
| 70 | *Cytheromorpha macroincisa*, new species |
| 71 | *Cytheropteron talquinensis* Puri, 1954 |
| 72 | *C.? yorktownensis* (Malkin, 1953) |
| 75 | *Cytherura howei* (Puri, 1954) |
| 76 | *Cytherura* sp. D |
| 77 | *C. reticulata* Edwards, 1944 |
| 78 | *Thaerocythere schmidtae* (Malkin, 1953) |
| 80 | *Cytherura wardensis* Howe and Brown, 1935 |
| 82 | *Hulingsina* sp. F |
| 83 | *Cytherura* sp. L |
| 84 | *Cytherura* sp. M |
| 85 | *Cytherura* sp. N |
| 89 | *Echinocythereis planibasalis* (Ulrich and Bassler, 1904) |
| 90 | *E. leecreekensis*, new species |
| 91 | *Eucythere declivis* (Norman, 1865) |
| 92 | *E. gibba* Edwards, 1944 |
| 94 | *E. triangulata* Puri, 1954 |
| 96 | *Eucythere* sp. F |
| 98 | *Peratocytheridea bradyi* (Stephenson, 1938) |
| 99 | *P. sandbergi*, new species |
| 104 | *Peratocytheridea* sp. J |
| 105 | *Cytheridea* aff. *C. virginiensis* (Malkin, 1953) |
| 106 | *C. campwallacensis*, new species |
| 107 | *C. virginiensis* (Malkin, 1953) |
| 111 | *C. carolinensis*, new species |
| 114 | *Hirschmannia? quadrata*, new species |
| 115 | *H.? hespera*, new species |
| 121 | *Leptocythere nikraveshae* Morales, 1966 |
| 125 | *Loxoconcha* sp. C |
| 126 | *L. purisubrhomboidea* Edwards, 1953 |
| 127 | *L. edentonensis* Swain, 1951 |
| 128 | *Hulingsina* sp. C |
| 130 | *Loxoconcha* sp. H |
| 131 | *L. reticularis* Edwards, 1944 |
| 132 | *Cytherura forulata* Edwards, 1944 |
| 133 | *Loxoconcha* sp. M |
| 136 | *L. matagordensis* Swain, 1955 |
| 138 | *Microcytherura similis* (Malkin, 1953) |
| 139 | *M. choctawhatcheensis* (Puri, 1954) |
| 140 | *M. expanda*, new species |
| 141 | *Microcytherura* sp. D |
| 143 | "*Pontocythere*" sp. I |
| 145 | *Microcytherura* sp. H |
| 147 | *Microcytherura* sp. M |
| 149 | *M. minuta*, new species |
| 150 | *Muellerina ohmerti*, new species |
| 151 | *M. bassiounii*, new species |
| 152 | *M. wardi*, new species |
| 153 | *M. blowi*, new species |
| 155 | "*Pontocythere*" sp. J |
| 156 | *Hulingsina glabra* (Hall, 1965) |
| 157 | *Muellerina canadensis petersburgensis*, new subspecies |
| 160 | *Muellerina* sp. P |
| 162 | *Murrayina macleani* Swain, 1974 |
| 163 | *M. barclayi* McLean, 1957 |
| 164 | *Murrayina* sp. E |
| 165 | *Radimella confragosa* (Edwards, 1944) |
| 166 | *Neocaudites triplistriatus* (Edwards, 1944) |
| 167 | *N. variabilus*, new species |
| 169 | *Xestoleberis* sp. E |
| 172 | *Orionina vaughani* (Ulrich and Bassler, 1904) |
| 173 | *Proteoconcha jamesensis*, new species |
| 175 | *P. gigantica* (Edwards, 1944) |
| 177 | *Proteoconcha* sp. Z |
| 178 | *P. mimica* Plusquellec and Sandberg, 1969 |
| 182 | *Paracyprideis* sp. C |
| 184 | *Paracypris* sp. B |
| 188 | *Paracytheridea cronini*, new species |
| 189 | *P. altila* Edwards, 1944 |
| 190 | *P. rugosa* Edwards, 1944 |
| 192 | *Paracytheroma stephensoni* (Puri, 1954) |
| 193 | *Cytherura* sp. |
| 194 | *Cytherura* sp. U |
| 196 | *Paradoxostoma delicata* Puri, 1954 |
| 198 | *Paradoxostoma* sp. E |
| 200 | *Paranesidea? laevicula* (Edwards, 1944) |
| 201 | *Paranesidea* sp. B |
| 205 | *Propontocypris* sp. D |
| 206 | *Proteoconcha multipunctata*, sensu lato |
| 207 | *Leptocythere* sp. E |
| 215 | *Pseudocytheretta burnsi* (Ulrich and Bassler, 1904) |
| 216 | *Loxoconcha* sp. T |
| 217 | *Cushmanidea* cf. *C. seminuda* (Cushman, 1906) |
| 223 | *Paracytheridea mucra* Edwards, 1944 |
| 224 | *Pterygocythereis inexpectata* (Blake, 1929) |
| 226 | *Puriana rugipunctata* (Ulrich and Bassler, 1904) |
| 227 | *P. carolinensis*, new species |
| 228 | *P. convoluta* Teeter, 1975 |
| 229 | *P. mesacostalis* (Edwards, 1944) |
| 230 | "*Pontocythere*" sp. G |
| 236 | *Sclerochilus* sp. B |
| 238 | *Actinocythereis captionis*, new species |
| 239 | *A. marylandica* (Howe and Hough, 1935) |
| 240 | *A. mundorffi* (Swain, 1951), small form |
| 241 | *A. dawsoni* (Brady, 1870) |
| 243 | *Acuticythereis laevissima* Edwards, 1944 |
| 250 | *Cytheromorpha? curta* Edwards, 1944 |
| 257 | *Microcytherura* sp. P |
| 309 | *Neocaudites angulatus*, new species |
| 312 | *Microcytherura* sp. R |

| Code | Species |
|---|---|
| 316 | *Cytherura* sp. W |
| 317 | *C. elongata* Edwards, 1944 |
| 318 | *Anchistrocheles* sp. C |
| 319 | *Bensonocythere* sp. OO |
| 320 | *Bensonocythere* sp. PP |
| 321 | *Cytherella* sp. B |
| 322 | *Cytheromorpha* sp. I |
| 323 | *Cytherura* sp. AA |
| 324 | *Peratocytheridea setipunctata* (Brady, 1869) |
| 326 | *Leptocythere* sp. F |
| 327 | *Paracytheridea* sp. F |
| 328 | *Neocaudites subimpressus* (Edwards, 1944) |
| 329 | *Bensonocythere* sp. QQ |
| 330 | *Bensonocythere* sp. RR |
| 331 | *Hermanites ascitus*, new species |
| 340 | *Cytherura* sp. BB |

## Biostratigraphy at the Lee Creek Mine

Figure 2 shows two major clusters of samples, labelled I and II, and four principal subclusters, labelled A–D (sample 16 tends to cluster at a low level because of relatively low diversity; the same is true to a lesser extent of sample 1). Samples 1–9 from the Yorktown Formation are faunally more similar to each other than to samples 10–16 from the Croatan Formation.

Thus, the major faunal discontinuity is between samples 9 and 10, and the Yorktown-Croatan contact may represent the major hiatus in the section above the base of the Yorktown. This conclusion is contrary to that of Welby and Leith (1969) who stated that the major break in the part of the mine section treated in the present study is between Gibson's (1967) units 2 and 3 of the Yorktown, that is, between samples 6 and 7 of this study.

Clusters A, B, C, and D indicate that recognizable faunal packages are found within each of the major clusters. Samples 1–7 from the lower 12 feet (3.6 m) of the Yorktown (units 1–3 of Figure 2) group together, and samples 8 and 9 from unit 4 from the upper part of the formation form another cluster. The latter two samples are each composites of samples containing similar faunas taken at virtually the same stratigraphic position but at different times. The interval below sample 8 and above sample 7 contained only a few poorly preserved ostracodes, none of which could be identified.

Sample 10 was taken from a 4-foot (1.2-m) interval in a 12-foot (3.6-m) thick bed of differentially indurated burrowed sand (unit 5) assigned to the Croatan; the irregularly shaped, indurated sandstone blocks are scattered throughout the unit but concentrated at the top. This sample groups faunally with those from the lower part (unit 6) of the very macrofossiliferous bed above. Samples from the upper part of this bed (unit 7) form subcluster D. The two parts of the bed are differentiated by the number of large mollusk shells that they contain: the lower part (unit 6) contains many, the upper part (unit 7), few. Small shells are abundant in both, but comminuted shell is more common or predominant in unit 7. The upper few feet of section below nonmarine Pleistocene ("Cherry Point" unit of DuBar, Solliday, and Howard, 1974) is a dark blue unfossiliferous sandy clay (unit 8) in undulating contact with unit 7; its stratigraphic relationship is unclear, and it is questionably referred to the Flanner Beach Formation (upper Pleistocene).

Opposite the R-mode dendrogram in Figure 3, the ranges of the 85 taxa in the 16 samples are given. These taxa, as well as those that occur in all or only one of the samples, are listed alphabetically and by code number (pp.85–90). At the top left of Figure 3 is a dendrogram summarizing the Q-mode results seen in Figure 2. For convenience in discussion, the R-mode subclusters of Figure 3 are labelled A–P, and the major clusters, I–IV Cluster I consists of species that occur chiefly in the Yorktown in the mine, and clusters II and IV are composed of species occurring principally in the Croatan. Cluster III is composed of species that occur in both the Yorktown and Croatan.

Subcluster D consists of species restricted to the samples of Q-mode subcluster A. R-mode subcluster C contains species that mostly occur throughout Q-mode subcluster A and extend into B and, in part, also into C, whereas R-mode subcluster B represents species that are found in the stratigraphically higher samples of Q-mode subclusters A and B.

Subcluster H consists of species that occur

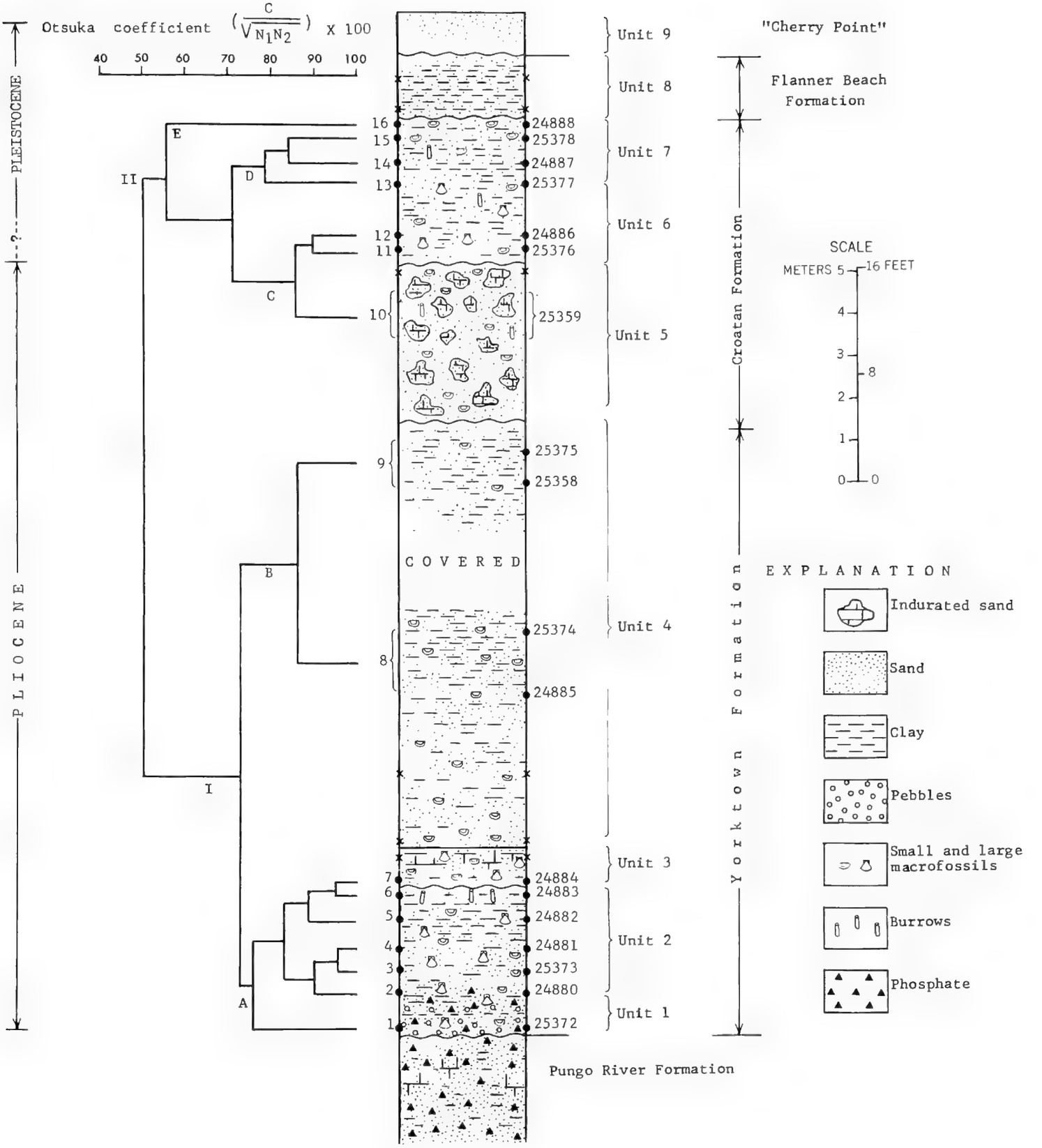


FIGURE 2.—Location of collections, general lithology, and results of Q-mode cluster analysis of the Yorktown and Croatan samples collected in the southwestern part of the Lee Creek Mine. Units 1–9 are the major lithologic units; the 5-digit numbers to the immediate right of the stratigraphic column are USGS Cenozoic locality numbers; the collection points are indicated by dots, except for nonmicrofossiliferous samples, which are indicated by X; the individual and composite samples (1–16) used in the multivariate analysis are indicated to the left of the column. The faunal relationships are indicated by the dendrogram, which was obtained by an unweighted pair-group cluster analysis of a matrix of Otsuka similarity coefficients. This procedure demonstrated two major clusters, indicated by the numerals I and II, and four principal subclusters, A–D, with a less clearly marked subcluster, E.

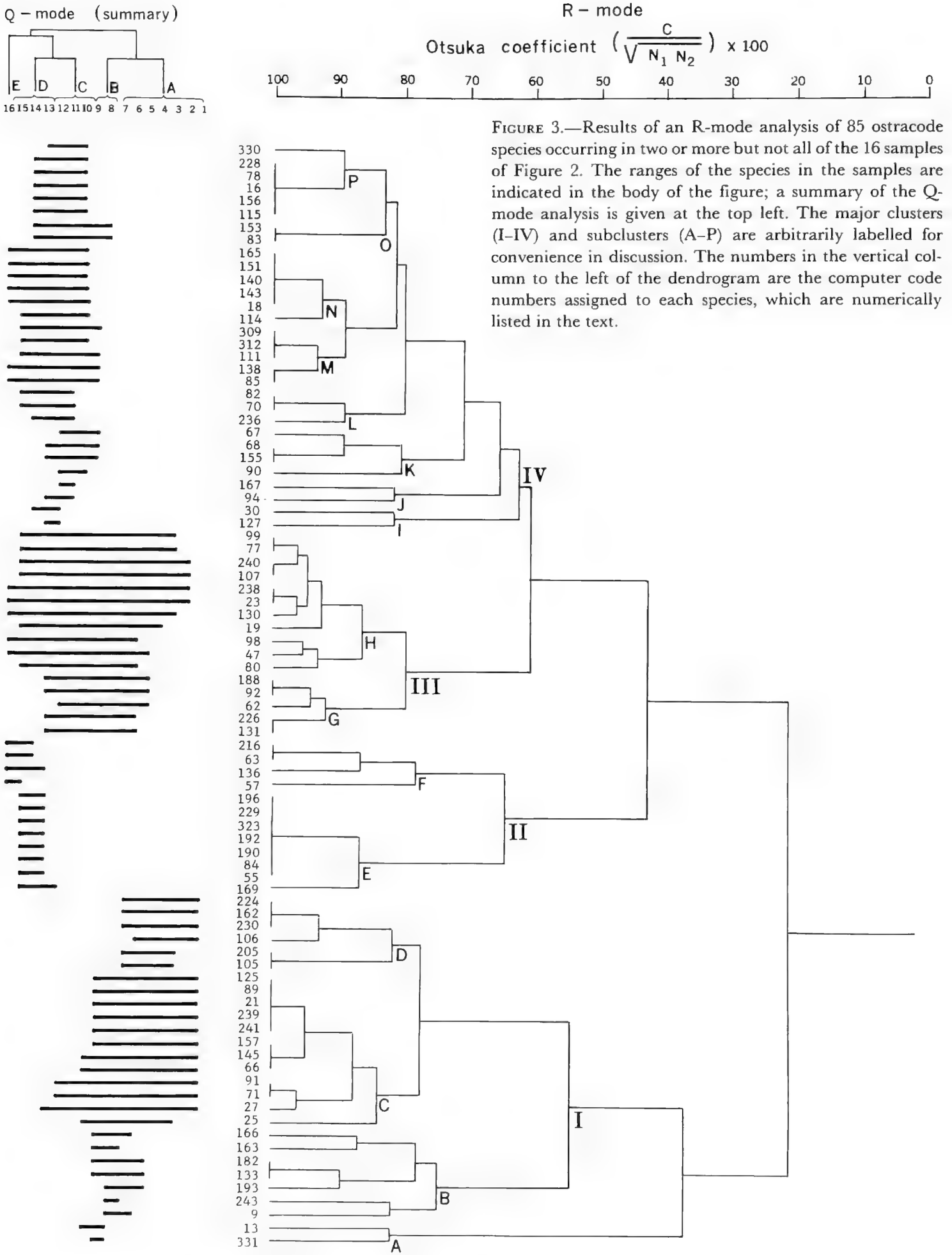


FIGURE 3.—Results of an R-mode analysis of 85 ostracode species occurring in two or more but not all of the 16 samples of Figure 2. The ranges of the species in the samples are indicated in the body of the figure; a summary of the Q-mode analysis is given at the top left. The major clusters (I–IV) and subclusters (A–P) are arbitrarily labelled for convenience in discussion. The numbers in the vertical column to the left of the dendrogram are the computer code numbers assigned to each species, which are numerically listed in the text.

through most of the section in the mine, and subcluster G, those that occur in the upper part of the Yorktown and the Croatan.

Subclusters I through P of cluster IV contain species that are present in the samples of Q-mode clusters C and D, with some occurrences in Q-mode subcluster B. R-mode cluster II comprises species that are largely restricted to the upper part of the Croatan and are, therefore, responsible for Q-mode subcluster D.

## Relative Stratigraphic Positions of Lee Creek Beds

### Correlations with Localities to the North

Samples from the Yorktown and Croatan formations in the Lee Creek Mine have high similarity values with those from localities farther north in North Carolina and Virginia (Figure 4) and can be assigned to the three assemblage zones proposed by Hazel (1971a).

Samples 1–4 from units 1 and 2 (Figure 2) can be confidently placed in the *Pterygocythereis inexpectata* assemblage zone (Figure 4). The faunal change from the *Pterygocythereis inexpectata* assemblage zone to the younger *Orionina vaughani* assemblage zone is one of gradation, apparently mostly climatically controlled (Hazel, 1971b:372), and samples 5, 6, and 7 are intermediate in composition. For example, they have a combined average similarity of 84.1 with samples 2, 3, and 4, and 81.1 with samples 8 and 9. Samples 5, 6, and 7 cluster with samples 2, 3, and 4 when the Lee Creek samples are analyzed separately, but they cluster with those of the *Orionina vaughani* assemblage zone when Yorktown samples from other areas are added (Hazel, 1971a:2–7).

Samples 8 and 9 from unit 4 represent the *Orionina vaughani* assemblage zone. Sample 9 represents beds not sampled in the previous study (Hazel, 1971a:7). However, the presence of the species *Murrayina barclayi* (McLean, 1957), *Echinocythereis planibasalis* (Ulrich and Bassler, 1904), and *Actinocythereis dawsoni* (Brady, 1870), suggests that unit 4 is no younger than the middle *Orionina vaughani* assemblage zone. The equivalent of the uppermost part of the classic Yorktown of the type area is seemingly missing at Lee Creek.

If sample 10, which is from a 3- or 4-foot (0.9- or 1.2-m) interval in the upper middle part of unit 5, is representative of the assemblage of the entire unit, then this unit is early *Puriana mesacostalis* assemblage zone in age, as based on its faunal similarity with the overlying samples and on the biostratigraphic fidelity values of the contained species (Hazel, 1971a:5, 6). Units 6 and 7 are also placed in the *Puriana mesacostalis* assemblage zone; the distinct cluster (D) formed by samples 13–15 suggests that the assemblage zone is divisible, but this very probably only reflects ecological differences between the upper and lower part of the bed. Units 5–7, as far as is known, are younger than deposits in the type area of the Yorktown, except for the one locality at Yadkin, Virginia, assigned to the Yorktown by Hazel (1971a, fig. 3), which has a *P. mesacostalis* assemblage zone. Also, the beds assigned to the Croatan here are correlated with those cropping out along the Chowan River in North Carolina in the vicinity of Colerain and Mt. Gould landings, which have been assigned to the Yorktown Formation by various authors. The beds along the Chowan River and those of the *Puriana mesacostalis* assemblage zone locality at Yadkin must be investigated further to ascertain which formation(s) is represented. (These beds have recently been assigned to the Chowan River Formation, named by Blackwelder (1981b) after this project had been completed.)

### Correlations with Localities to the South

Many Yorktown and Croatan species are present in sediments of similar age to the south, although the ostracode assemblages are in general somewhat different in their overall aspect. Some of these species have limited stratigraphic ranges, and some concurrent range zones are useful in recognizing the chronozones of the three assemblage zones of Hazel (1971a) and in correlating the Yorktown with formations in the Carolinas south of the Neuse River and in Georgia and Florida.

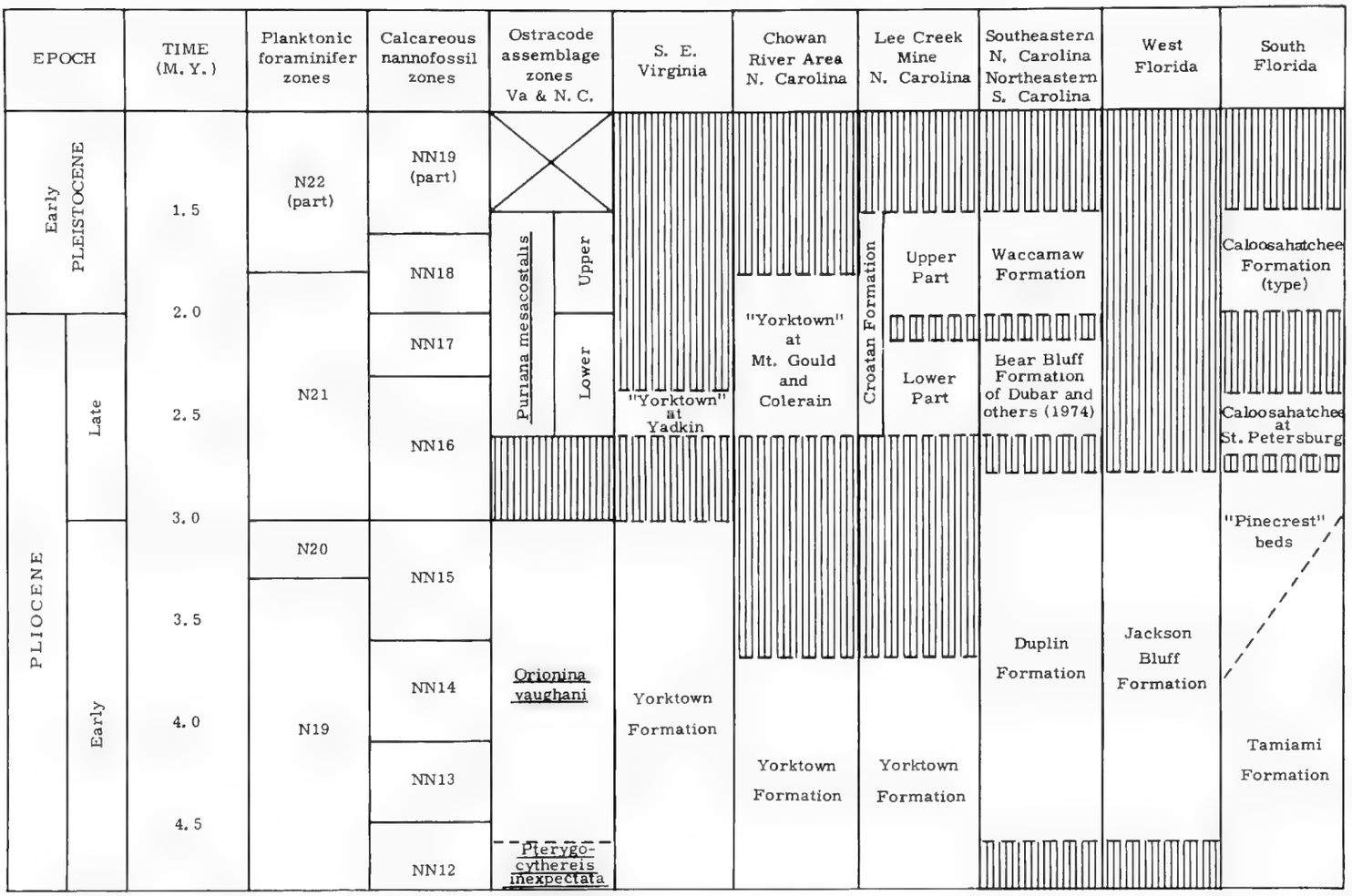


FIGURE 4.—Suggested correlation of the Yorktown and Croatan formations at the Lee Creek Mine with other Coastal Plain lithostratigraphic units and with planktonic foraminifer and nannofossil zonations (time-scale and planktonic organism zones from Berggren and van Couvering, 1974). The planktonic zonations are shown for comparative purposes. Zone-diagnostic planktonic microfossils are generally rare in the formations indicated in the figure.

Care must be taken, however, in using certain kinds of species for the purpose of correlation in the Atlantic Coastal Plain. During Yorktown and Croatan time, the marine climate changed from possible mild-temperate to subtropical conditions in the region of Yorktown and Croatan outcrop (Hazel, 1971b:373), perhaps in response to the closing of the Isthmus of Panama, which would affect the Gulf Stream system (Berggren and Hollister, 1974:158, 175; Emiliani, Gartner, and Lidz, 1972; Casey, McMillen, and Bauer, 1975). A climatic shift in the same direction is to be expected in the southern part of the Atlantic Coastal Plain.

Cryophilic species, then, should be expected to have longer stratigraphic ranges in the north than in the south; the reverse would be true for thermophilic species. Cognizance of the paleoclimatologic framework can be very important in biostratigraphic interpretation.

A large collection of samples from Coastal Plain units to the south has been made, but the studies are incomplete. A multivariate analysis of the data is planned that, it is hoped, will lead to the establishment of regionally useful assemblage zones, such as were proposed for the Virginia-northern North Carolina region (Hazel, 1971a). In addition, work is in progress on a paper delin-

eating the most useful ostracode range and concurrent range zones of the Pliocene and Pleistocene of the middle Atlantic Coastal Plain. This study and those of previous workers (Edwards, 1944; Pooser, 1965; Swain, 1968; Puri, 1953b; Puri and Vanstrum, 1971) suggest certain correlations, which are summarized below.

Beds referable to the *Pterygocythereis inexpectata* ostracode assemblage zone, which in the molluscan zonation of Mansfield (1929, 1943) would approximate the *Placopecten clintonius* zone (zone 1), are either uncommon or difficult to recognize in the southern Atlantic Coastal Plain. The Raysor Marl of Cooke (1936), known from one locality on the Edisto River, South Carolina, and now generally included in the Duplin Formation has been said to contain a fauna of this age. Washings from the original Raysor Marl collection of Cooke (1936) contain *Pterygocythereis inexpectata* (Blake, 1933), *Pseudocytheretta burnsi* (Ulrich and Bassler, 1904), *Malzella evexa*, new species; *Actinocythereis marylandica* (Howe and Hough, 1935), *Cytheropteron? yorktownensis* (Malkin, 1953), *Cytheridea virginiensis* (Malkin, 1953), *Muellerina ohmerti*, new species, *Muellerina wardi*, new species, and other species. This temperate assemblage is of early Yorktown age (chronozone of the *Pterygocythereis inexpectata* assemblage zone or lower *Orionina vaughani* assemblage zone). The Duplin Formation near Magnolia, North Carolina, contains a large ostracode assemblage suggestive of a middle or late *Orionina vaughani* assemblage zone age. It should be noted here that the statement attributed to the writer in Berggren and Van Couvering (1974:125), that the Duplin correlates with rocks containing planktonic foraminifers of zone N12 (middle Miocene), contains an unfortunate typographical error; it should read "N19" (Pliocene) rather than "N12."

Units 3, 4, and the upper part of 2 of the Yorktown in the Lee Creek Mine are placed in the *Orionina vaughani* assemblage zone. In these beds, *Neocaudites triplistriatus* (Edwards, 1944), *Neocaudites angulatus*, new species, and *N. subimpressus* (Edwards, 1944), first appear, and several typical Yorktown forms (subclusters B and C of Figure 3) are last seen. The former all occur farther south, but few of the latter do.

*Malzella conradi* (Howe and McGuirt, 1935), which ranges as high as the lower part of the *Puriana mesacostalis* assemblage zone, occurs in the lower Duplin, Jackson Bluff, Red Bay, and Tamiami formations. *Murrayina barclayi* McLean, 1957, which occurs in the *Orionina vaughani* assemblage zone and older units, has been traced as far south as Orlando, Florida, where it occurs in rocks of Jackson Bluff age (also see Pooser, 1965:60). *Bensonocythere rugosa*, new species, occurs in the Yorktown and the lower part of the Croatan; in the Duplin Formation, and the Bear Bluff Formation of DuBar et al. (1974:156) in the Carolinas; and the Tamiami Formation in the subsurface of southern Florida.

The equivalent of the Bear Bluff Formation of North and South Carolina of DuBar et al. (1974) is probably represented at Lee Creek by the lower part of the Croatan Formation (unit 5). Ostracodes have been studied from the Bear Bluff Formation at Calabash, North Carolina, and from the subsurface near Bayboro, South Carolina. The Bear Bluff assemblage is very similar to that of the overlying Waccamaw Formation but contains the typical Yorktown-Duplin forms, *Bensonocythere rugosa*, new species, and *Malzella conradi* (Howe and McGuirt, 1935). The two species are known to extend only into the lower part of the *Puriana mesacostalis* assemblage zone. Both occur in sample 10 from the lower part of the Croatan, with an assemblage that is otherwise very similar to that of the upper part of the Croatan.

According to DuBar et al. (1974:156–157) the Bear Bluff occurs primarily in the subsurface and is unconformable with the overlying Waccamaw and possibly with the underlying Duplin Formation, where the latter is present; they indicated that the Bear Bluff macrofauna is transitional between that of the Duplin and Waccamaw formations.

Units 6 and 7 of the Croatan in the Lee Creek Mine are placed in the *Puriana mesacostalis* assemblage zone and contain an evolutionarily advanced form (larger, more elongated) of *Loxocon-*

*cha edentonensis* (Swain, 1951), which is also known from the Waccamaw Formation. *Caudites paraasymmetricus*, new species (=*C. sellardsi* of Swain, 1968), occurs in unit 7. This distinctive species has been found previously only in the Waccamaw Formation and in its type locality of the Caloosahatchee Formation. It appears then that at least the upper part of the Croatan at the mine correlates with part or all of the Waccamaw and the type Caloosahatchee (DuBar, 1974:220, DuBar et al., 1974:164).

## Correlation of the Yorktown and Croatan Formations with a Time Scale

The correlations suggested in the above discussion were based on benthic species endemic to North America. Because none of these taxa occur in stratotypes of the upper Tertiary stages of western Europe, they provide no data for direct correlation with European deposits (Waller, 1969:92). Estimates of age for the Yorktown and Croatan samples, therefore, must be based on (1) finding in these formations more mobile organisms that have a wider distribution and may occur in Europe, or (2) biostratigraphic correlation with rocks that do contain such organisms, or (3) obtaining radiometric dates for the Lee Creek or demonstrably correlative deposits.

Planktonic foraminifers are not diverse in the Yorktown at the Lee Creek Mine above the basal bed (Gibson, 1967:638; Akers, 1972:34). Gibson (1967:637) indicated that the planktonic assemblage from the lowermost beds was of late Miocene aspect; he later (1971:10) concluded that the beds belonged to Blow's (1969) zone N16. This zone, according to Berggren and Van Couvering (1974, figs. 5, 11), is late Miocene in age and lasted from about 10.5 to 8.5 million years ago (mya). However, only one of the species listed by Gibson (1967:637) would be inconsistent with a younger age, and two of the species would be inconsistent with a pre-Pliocene age.

Akers (1972) identified 17 species of planktonic foraminifers from the Yorktown at Rice's pit in Hampton, Virginia (loc. 11 of Hazel, 1971a:11). He placed the Yorktown at the pit in zone N19, pointing out that the assemblage is essentially the same as that of the Jackson Bluff Formation of western Florida. The ostracode assemblage in the Yorktown at Rice's pit indicates placement in the *Orionina vaughani* assemblage zone (Hazel, 1971a, fig. 3). The Tamiami Formation in the subsurface of the Miami area also carries a zone N19 planktonic foraminifer assemblage (identified by M. Ruth Todd, U.S. Geological Survey), as well as ostracodes indicating correlation with the Jackson Bluff Formation (at least the *Ecphora* zone of the Jackson Bluff) and the Yorktown. Present in the Tamiami Formation are common *Orionina vaughani* assemblage zone constituents such as *Malzella conradi* (Howe and McGuirt, 1935), *Malzella evexa*, new species, *Orionina vaughani* (Ulrich and Bassler, 1904), *Bensonocythere rugosa*, new species, *Actinocythereis dawsoni* (Brady, 1870), *Cytheropteron? yorktownensis* Malkin, 1953, and *Puriana rugipunctata* (Ulrich and Bassler, 1904). According to Berggren (1973), zone N19 lasted from about 4.8 to 3.3 mya. The lowermost Yorktown beds at the Lee Creek Mine, however, are clearly older than those at Rice's pit (Hazel, 1971a, fig. 3).

The Red Bay Formation of Puri and Vernon (1964) in western Florida belongs in planktonic zone N17, according to Akers (1972:13). The ostracode and molluscan assemblages of Puri and Vernon's Red Bay Formation (=*Arca* zone of older literature) also indicate that Red Bay is older than the Jackson Bluff Formation. Based on such mollusks as *Chesapecten middlesexensis* (Mansfield, 1929; Ward and Blackwelder, 1975; Druid Wilson, pers. comm., 1973), rocks below the Tamiami Formation in the subsurface of southern Florida can be correlated with the Red Bay and with the Eastover Formation of Virginia, which is stratigraphically below the Yorktown. The ostracode *Otikocythere redbayensis* (Howe and Brown, 1935) is known only from Puri and Vernon's Red Bay Formation and from subsurface deposits on the Eastern Shore of Maryland judged to belong to the lower Eastover Formation. This evidence suggests that the Yorktown is younger than zone N17 which, according to Berggren (1972a, fig. 7; 1973), was about 8.5 to 5.0 mya. Berggren (1973) also presented evidence that the

Miocene-Pliocene boundary is at about 5.0 mya, and that this, for all practical purposes, is equivalent to the base of zone N18. These findings lead to the conclusion that the lowermost beds of the Yorktown at the Lee Creek Mine are at least as young as zone N18 and are therefore Pliocene in age.

Recently, Andrews (1980) has found the diatom species *Thalassiosira oestrupii* (Ostenfeld) in the upper part of the lower Eastover Formation (upper Claremont Manor Member). According to Andrews (1980:20, 22) this indicates that at least the upper part of the Claremont Manor Member and the overlying Cobham Bay Member of the Eastover Formation are also early Pliocene in age.

On the basis of calcareous nannofossils, Akers and Koeppel (1973) concluded that the Yorktown at the Lee Creek Mine was the chronostratigraphic equivalent of planktonic foraminifer zone N20 rather than N19. However, more recent work indicates that N20 is equivalent to upper N19 (for example, Poore, 1979).

Glauconite, from a sample containing an assemblage typical of the *Orionina vaughani* assemblage zone (collected 18 feet (5.5 m) above the beach and 1.3 miles (2.1 km) below the mouth of Grove Creek on the left bank of the James River, James City County, Virginia), gives a K/Ar age of 4.4±0.2 my. This indicates an early Pliocene age for the sample and apparently corroborates the biostratigraphic dating of the Yorktown as early Pliocene (zone N19).

Using the He/U method, Bender (1973) dated corals from the Caloosahatchee Formation of southern Florida. Five of the dates were based on specimens taken from the upper part of the Caloosahatchee (Bee Branch Limestone or Ayers Landing Members of DuBar, 1958) in the type area of the formation, and a sixth was based on a specimen from farther north at St. Petersburg. The five dates from the type area average 1.84 my and have an observed range of 1.78 to 1.89 mya. The upper part of the Croatan in the mine biostratigraphically correlates with the type Caloosahatchee and the Waccamaw Formation. The Caloosahatchee sample from St. Petersburg, which was dated at 2.53 my, contains a molluscan assemblage (Druid Wilson, pers. comm., 1974) indicative of an age younger than the "Pinecrest" beds of Olsson (1964), and several of the distinctive forms found in the Caloosahatchee in its type area are conspicuously absent.

M.L. Bender, University of Rhode Island, in cooperation with the U.S. Geological Survey, has dated corals from the Waccamaw, Croatan, Yorktown, and other upper Cenozoic Coastal Plain units using the He/U technique (see Bender, 1973; Blackwelder, 1981a:17, 24; 1981b:10). The results for some samples are important to the present study. Coral from the lower part of the Croatan (upper part of unit 5 from the north wall of the mine) gives a date of about 2.4 my. Coral from sample 18 of Hazel (1971a:11; fig. 3) from the "Yorktown" near Mt. Gould Landing, North Carolina, gives a date of about 1.91 my.

Hazel (1971a:7) suggested that the "Yorktown" beds near Mt. Gould correlate with what is termed unit 6 in the Croatan Formation in the present study. The fossiliferous beds from the lower part of the exposure at Colerain Landing are younger than the Yorktown Formation of the type area and the Lee Creek Mine, and older than those from near Mt. Gould; therefore, they are most probably correlated with the lower part of the Croatan (unit 5) of the mine.

The radiometric data (Bender, 1973; in litt., 1975) coupled with the biostratigraphy suggest that the Croatan Formation and its correlatives were deposited between about 1.5 and 2.6 mya and that the contact between units 5 and 6 in the mine may approximate 2.0 my. The Yorktown Formation probably was deposited between about 2.6 and 4.8 mya. The youngest part of the Yorktown in the mine is apparently no younger than the middle *Orionina vaughani* assemblage zone. A 3.7- to 4.8-my age range for the Lee Creek Yorktown is not unreasonable.

In connection with the placement of the Pliocene-Pleistocene boundary in the mine, it should be noted that there is considerable controversy as to the radiometric age of the Pliocene-Pleistocene boundary. The Pleistocene should be recognized in a manner similar to all other series of the

Phanerozoic, that is, by correlation of localities with the type area by whatever techniques that give temporally meaningful correlations. There is little logic to the argument that the Pleistocene be recognized by climatic deterioration.

At present, many authors accept the appearance of the planktonic foraminifer *Globorotalia truncatulinoides*, which apparently first appears in the type area of Calabria near the base of the Calabrian Stage, as evidence of the beginning of the Pleistocene. Berggren et al. (1967) presented the results of a study of a deep-sea core from the south-central Atlantic, in which micropaleontologic and paleomagnetic analyses were performed. Berggren indicated that the evolutionary transition from *G. tosaensis* to *G. truncatulinoides* occurred in this borehole and that the first evolutionary appearance of *G. truncatulinoides* was at 500 cm, paleomagnetically dated at 1.85 my. Later refinement by Berggren and others (Berggren and van Couvering, 1974:88) placed this event at 1.8 my, thereby providing the basis for this commonly cited date for the beginning of the Pleistocene.

Parker (1973:280) also studied the foraminifers of the same Atlantic core and opined that at least some of the *G. tosaensis* specimens identified by Berggren were referable to a variant of *G. crassaformis* called "*ronda*." However, *G. tosaensis* and *G. truncatulinoides* occur in the core, and Parker's findings in effect indicate only that the Pliocene-Pleistocene boundary championed by Berggren is some 85 cm below where Berggren (1967) placed it. This suggests a revision of the date for the Pliocene-Pleistocene boundary from 1.8 to 2.0 mya.

Not all workers are willing to accept that *Globorotalia truncatulinoides* is useful in marking the beginning of the Pleistocene or that the Pleistocene began at about 2.0 mya. In open-ocean sediments, however, abundant *G. truncatulinoides* does seem to be a useful criterion, although planktonic foraminifers are generally not abundant in the outcropping sublittoral upper Cenozoic deposits of the Atlantic Coastal Plain.

If the suggested placement of the Pliocene-Pleistocene boundary in Figure 4 is correct, then the unconformity at about 2.8 my in the Atlantic Coastal Plain may correlate with the first cooling event documented in deep-sea cores (Beard, 1969; Berggren, 1972b).

## Locality Data

The stratigraphic position and U.S. Geological Survey number of the Lee Creek Mine samples used in this study are indicated in Figure 2. The comparative material from elsewhere in the Yorktown Formation has been given by Hazel (1971a). Comparative material from farther south in the Coastal Plain in North Carolina, South Carolina, Georgia, and Florida consists of more than 300 U.S. Geological Survey collections from the Duplin, Waccamaw, Bear Bluff, Jackson Bluff, Tamiami, and Caloosahatchee formations and Olsson's "Pinecrest" beds (Hazel, 1977; Cronin and Hazel, 1980; Cronin, 1980).

## Systematics

Because of the large number of new species involved in the study, the writer has presented the systematic part of the paper as follows: With one exception, *Peratocytheridea setipunctata* (Brady, 1869), only the new species group taxa are treated in formal systematics. For these, a differential diagnosis, but no description as such, is presented. The diagnoses are supplemented by what the writer considers to be generally excellent scanning-electron photomicrographs presented as stereopairs. This approach is taken because the writer believes there is considerable redundant and nondiagnostic information in most ostracode species descriptions. Features that are general characteristics of the genus or family and those that can be clearly observed on photomicrographs need not be described. I believe that the diagnoses presented here, coupled with the illustrations, will be sufficient to indicate my concept of the taxa to other workers.

Most of the species previously described from the Yorktown and Croatan and some that are left in open nomenclature are also illustrated. An alphabetical listing and a numerical computer

code list of the taxa used in the computer analyses are presented (pp. 85–90); in the alphabetical list, occurrence data are followed by number of the plate and figure in which each species is illustrated. A checklist of taxa treated formally in this report also follows, reflecting the hierarchic classification used.

Although all the ostracode subfamilies found in the Yorktown and Croatan have been studied and the species delineated by the author, descriptions have not been prepared for some of them; these new taxa are listed in open nomenclature. Major groups in this category are the loxoconchids (except for *Hirschmannia*), and the cytherurids, *Hulingsina*, *Cushmanidea*, *Neocytherideis*, *Leptocythere*.

This study is a contribution from a U.S. Geological Survey program to document the Pliocene and Quaternary ostracodes of the Atlantic continental margin (Hazel, 1967, 1968a, 1970, 1971a, 1971b, 1975a, 1975b; Hazel and Valentine, 1969; Valentine, 1971). The specimens used to illustrate the species were selected from the Yorktown and Croatan formations at the Lee Creek Mine, as well as from various other formations and modern samples. The locality data for the illustrated specimens are given in the figure descriptions. All illustrated specimens are deposited in the USNM collections of the National Museum of Natural History, Smithsonian Institution, Washington, D.C.

Abbreviations used in the tabulations of the dimensions are as follows: N, number of specimens measured; M, mean; sd, standard deviation; OR, observed range; and V, coefficient of variation.

## Checklist

Order PODOCOPIDA Müller, 1894
- Suborder PODOCOPA Sars, 1865
  - Superfamily CYTHERACEA Baird, 1850
    - Family CYTHERIDEIDAE Sars, 1925
      - Subfamily CYTHERIDEINAE Sars, 1925
        - Genus *Cytheridea* Bosquet, 1852
          - *Cytheridea campwallacensis*, new species
          - *Cytheridea carolinensis*, new species
        - Genus *Peratocytheridea*, new genus
          - *Peratocytheridea setipunctata* (Brady, 1869)
          - *Peratocytheridea sandbergi*, new species
    - Family TRACHYLEBERIDIDAE Sylvester-Bradley, 1948
      - Subfamily TRACHYLEBERIDINAE Bradley, 1948
        - Tribe TRACHYLEBERIDINI Bradley, 1948
          - Genus *Actinocythereis* Puri, 1953
            - *Actinocythereis captionis*, new species
          - Genus *Neocaudites* Puri, 1960
            - *Neocaudites variabilus*, new species
            - *Neocaudites angulatus*, new species
        - Tribe PTERYGOCYTHEREIDINI Puri, 1957
          - Genus *Pterygocythereis* Blake, 1933
            - *Pterygocythereis alophia*, new species
      - Subfamily HEMICYTHERINAE Puri, 1953
        - Tribe AURILINI Puri, 1974
          - Genus *Malzella*, new genus
            - *Malzella evexa*, new species
        - Tribe ECHINOCYTHEREIDINI Hazel, 1967
          - Genus *Echinocythereis* Puri, 1953
            - *Echinocythereis leecreekensis*, new species
        - Tribe ORIONININI Puri, 1974
          - Genus *Caudites* Coryell and Fields, 1937
            - *Caudites paraasymmetricus*, new species
        - Tribe COQUIMBINI Ohmert, 1968
          - Genus *Muellerina* Bassiouni, 1965
            - *Muellerina ohmerti*, new species
            - *Muellerina canadensis petersburgensis*, new subspecies
            - *Muellerina bassiounii*, new species
            - *Muellerina wardi*, new species
            - *Muellerina blowi*, new species
        - Tribe THAEROCYTHERINI Hazel, 1967
          - Genus *Thaerocythere* Hazel, 1967
            - *Thaerocythere carolinensis*, new species
          - Genus *Hermanites* Puri, 1955
            - *Hermanites ascitus*, new species
          - Genus *Puriana* Coryell and Fields, 1953
            - *Puriana carolinensis*, new species
      - Subfamily CAMPYLOCYTHERINAE Puri, 1960
        - Tribe CAMPYLOCYTHERINI Puri, 1960
          - Genus *Proteoconcha* Plusquellec and Sandberg, 1969
            - *Proteoconcha jamesensis*, new species
        - Tribe LEGUMINOCYTHEREIDINI Howe, 1961
          - Genus *Bensonocythere* Hazel, 1967
            - *Bensonocythere bradyi*, new species
            - *Bensonocythere blackwelderi*, new species
            - *Bensonocythere gouldensis*, new species
            - *Bensonocythere ricespitensis*, new species
            - *Bensonocythere rugosa*, new species
    - Family CYTHERIDAE Baird, 1850
      - Subfamily CYTHERINAE Baird, 1850
        - Tribe CYTHERINI Baird, 1850
          - Genus *Cytheromorpha* Hirschmann, 1909
            - *Cytheromorpha incisa*, new species

*Cytheromorpha macroincisa*, new species
*Cytheromorpha suffolkensis*, new species
Genus *Microcytherura* Müller, 1894
*Microcytherura minuta*, new species
*Microcytherura expanda*, new species
Family LOXOCONCHIDAE Sars, 1865
Genus *Hirschmannia* Elofson, 1941
*Hirschmannia? hespera*, new species
*Hirschmannia? quadrata*, new species
Family PARACYTHERIDEIDAE Puri, 1957
Genus *Paracytheridea* Müller, 1894
*Paracytheridea cronini*, new species

## Genus *Cytheridea* Bosquet, 1852

### *Cytheridea campwallacensis*, new species

PLATE 2: FIGURES 1, 3, 4

*Anonocytheridea floridana* (Howe and Hough).—Malkin, 1953: 784, pl. 79: figs. 29, 30.
*Cytheridea* sp. B.—Hazel, 1971a:6, table 1, species 73.—Swain, 1974:14, pl. 1: figs. 11, 12 [not pl. 1: fig. 4].
*Cytheridea campwallacensis* Hazel, 1977:378, figs. 3, 5f, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Many shallow narrow fossae containing normal pore canals, thus possessing relatively smoother valve surfaces than *Cytheridea virginiensis*. On eight well-preserved specimens of *C. campwallacensis*, very short spines at the anterior and a single short spine in each valve at the posterior were observed. In contrast, *C. virginiensis* has 6 or 7 anterior spines on each valve and 2 spines connected by an extension of the valve between the spines (or a tab with spines at either end) at the posterior only in the right valve. The pattern of fossae is distinct from that shown by *Cytheridea virginiensis* (Plates 1, 2). Sexual dimorphism is strong in *C. campwallacensis* and weak in *C. virginiensis*.

HOLOTYPE.—A female right valve (Plate 2: figure 4), USNM 172619, from the lower part of the *Orionina vaughani* assemblage zone of the Yorktown Formation on the James River, Virginia (sample VA-7 of Malkin, 1953, pl. 79: fig. 29).

ETYMOLOGY.—From Camp Wallace, Virginia, on the James River, where the species occurs commonly.

DIMENSIONS (in microns).—The height statistics are biased toward right valves; 14 of the 18 specimens preserved well enough to measure were right valves.

| | Female | | Male | |
|---|---|---|---|---|
| | Length | Height | Length | Height |
| N | 11 | 11 | 7 | 7 |
| M | 825 | 480 | 879 | 477 |
| sd | 47 | 32 | 9 | – |
| OR | 775–900 | 450–550 | 862–888 | 450–520 |
| V | 5.7 | 6.7 | 1.1 | – |

AGE RANGE.—Early Pliocene.

DISTRIBUTION.—Lower and middle part of the Yorktown, *Pterygocythereis inexpectata* and lower *Orionina vaughani* assemblage zones in Virginia and North Carolina. Thirty-five specimens were found.

### *Cytheridea carolinensis*, new species

PLATE 3

*Cytheridea* sp. G.—Hazel, 1971a:6, table 1, species 76.
*Cytheridea carolinensis* Hazel, 1977:376, figs. 3, 5e, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Smaller than *C. virginiensis*, and with a more anterior anterodorsal angle, more weakly pitted surface, and fewer normal pore canals. Much smaller than *C. campwallacensis*, and the arrangement of normal pores is distinctly different. At least 5 anterior denticles; none were observed at the posterior. Three to 4 low ridges parallel the anterior margin in contrast to *C. campwallacensis* and *C. virginiensis*, in each of which there are only two.

HOLOTYPE.—A female left valve (Plate 3: figure 1), USNM 191357, from the *Puriana mesacostalis* assemblage zone of the Croatan Formation at the Lee Creek Mine, North Carolina (sample 15).

DIMENSIONS (in microns).—

| | Female | | Male | |
|---|---|---|---|---|
| | Length | Height | Length | Height |
| N | 9 | 9 | 2 | 2 |
| M | 617 | 361 | | – |
| sd | 23 | 25 | | – |
| OR | 588–650 | 325–400 | 638–650 | 350–362 |
| V | 3.8 | 7 | | – |

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—Upper part of the Yorktown Formation in Virginia and the Croatan Formation in North Carolina. More than 20 specimens have been found.

REMARKS.—The surface pits are wider and deeper on the older (early Pliocene) specimens assigned to the species.

### Genus *Peratocytheridea*, new genus

*Peratocytheridea* Hazel, 1977, figs. 3, 7h; table 1 [nomen nudum].

TYPE SPECIES—*Cytheridea setipunctata* Brady, 1869.

DIFFERENTIAL DIAGNOSIS.—In adult specimens, ventral margin is concave in the anterior half; carapace widest in the posterior half; the hinge holomerodont (with reversal of hingement in some species); dorsal adductor muscle scar elongated toward the anterodorsal and posteroventral areas.

REMARKS.—Distinct morphologic differences have been recognized between the North American Miocene to Holocene species referred to *Haplocytheridea* and the early Tertiary and late Cretaceous species referred to the genus (Morkhoven, 1963:278–281; Hazel, 1968b:126). The genus *Peratocytheridea* is proposed to accommodate some of these late Cenozoic species.

The species here referred to *Peratocytheridea* are more broadly rounded at the posterior than those referred to *Haplocytheridea*. They are widest in the posterior half, whereas *Haplocytheridea* is compressed posteriorly. The ventral margin of *Peratocytheridea* is concave in the anterior half and that of *Haplocytheridea*, in the posterior half. The dorsal adductor muscle scar in *Peratocytheridea* is elongated toward the anterodorsal and posteroventral areas. In at least the type species of *Haplocytheridea*, the dorsal adductor is not elongated. Under high magnification small denticles can be seen on the outer margin of the selvage, as well as at the outer margin of the valve at the anterior and posterior. This last characteristic may or may not be diagnostic.

The following species are assigned to *Peratocytheridea*:

*Cytheridea setipunctata* Brady, 1869; Pliocene to Holocene.
*C. (Haplocytheridea) bradyi* Stephenson, 1938; Pliocene to Holocene.
*C. (H.) wadei* Stephenson, 1938; Pliocene.
*Cytheridea kirkbii* Brady, 1866; Holocene.
*C. subovata* Ulrich and Bassler, 1904; late Oligocene to Miocene.
*Haplocytheridea bassleri* Stephenson of Puri (1953b, pl. 3, figs. 1–3); Miocene.
*H. placentiaensis* Teeter, 1975; Holocene.
*H. texana* Stephenson, 1944; late Oligocene.
*Peratocytheridea sandbergi*, new species; Pliocene.

The taxonomic positions of the Miocene Caribbean species assigned to *Haplocytheridea* by van den Bold (1965), the late Oligocene Gulf Coast forms studied by Butler (1963) and Poag (1974), and the younger early Miocene species "*H.*" *mansfieldi* (Stephenson, 1938) and "*H.*" *gardnerae* (Stephenson, 1938) are not clear at present (see Sandberg, 1964b).

The species here assigned to *Peratocytheridea* have a combined chronostratigraphic range of upper Oligocene to Holocene. *Haplocytheridea* is known from the Upper Cretaceous to the upper Eocene and possibly Oligocene (Poag, 1972:68; 1974:49).

The well-known species, *Cytheridea setipunctata* Brady, 1869, is chosen as the type species. The soft parts for *Peratocytheridea setipunctata* have been illustrated by Sandberg (1970, figs. 3, 5, 7, 9).

### *Peratocytheridea setipunctata* (Brady, 1869), new combination

PLATE 4: FIGURE 4

*Cytheridea setipunctata* Brady, 1869:124, pl. 14: figs. 15, 16.
*Cytheridea (Haplocytheridea) ponderosa* Stephenson, 1938:133, pl. 23: fig. 10; pl. 24: figs. 1, 2.
*Cytheridea (Leptocytheridea) sulcata* Stephenson, 1938:139, pl. 23: fig. 2.
*Cytheridea puncticillata* Brady.—Tressler and Smith, 1948:11 [partim], pl. 1: fig. 2 [two juvenile specimens on USNM slide 87319 are probably *Peratocytheridea setipunctata*; as Sandberg (1964b:362) points out, the male specimen in the collection is a *Cyprideis*].

*Haplocytheridea bassleri* Stephenson.—Swain, 1955:617 [partim], pl. 59: fig. 9a [not pl. 59: fig. 9b, which is a *Cyprideis americana* (Sharp, 1908)].

[?] *Haplocytheridea bassleri* (Stephenson).—Puri and Hulings, 1957, fig. 11.

*Haplocytheridea* cf. *H. ponderosa* (Stephenson).—Curtis, 1960:482, pl. 2: fig. 9.

*Haplocytheridea ponderosa* (Stephenson).—Curtis, 1960:486, pl. 3: fig. 1.

*Haplocytheridea bassleri* (Stephenson).—Curtis, 1960:486, pl. 3: fig. 2.

[?] *Haplocytheridea ponderosa* (Stephenson).—Puri, 1960:110.

[?] *Haplocytheridea* cf. *H. nodosa* (Stephenson).—Puri, 1960: 110.

*Cyprideis floridana* Puri, 1960:100, pl. 2: fig. 5.

[?] *Anomocytheridea* cf. *A. floridana* (Howe and Hough).—Benda and Puri, 1962, pl. 3: fig. 32.

*Haplocytheridea gigantea* Benson and Coleman, 1963:27, pl. 3: figs. 10–14, fig. 14.

*Haplocytheridea setipunctata.*—Sandberg, 1964a:507, pl. 3: fig. 12; 1964b:361, pl. 1: figs. 10–14, pl. 2: figs. 1–4 [not *Haplocytheridea setipunctata* (Brady)].—Williams, 1966:21, figs. 5–11, 16 [=*Peratocytheridea bradyi* (Stephenson), 1938].—Morales, 1966:34, pl. 2: figs. 3a–c.—Hulings, 1967:643, fig. 3q.—Grossman, 1967:64a, pl. 11: figs. 4, 7, pl. 16:figs. 13–18 [not *Haplocytheridea setipunctata* (Brady)].—Engle and Swain, 1967:413, pl. 2: fig. 15 [=*Cyprideis americana* (Sharpe, 1908)].—Swain, 1968:7, pl. 1: figs. 5a–c; pl. 7: figs. 1a, b [=*Peratocytheridea sandbergi*, new species].—King and Kornicker, 1970:29, pl. 4: figs. 2a, b, pl. 13: figs. 9, 10, pl. 1b: figs. 7, 8.—Sandberg, 1970, figs. 5, 7, 9 [soft parts].—Krutak, 1971:16, pl. 2: figs. 6a, b.—Valentine, 1971, pl. 2: figs. 48, 49 [not *Haplocytheridea setipunctata* (Brady)].—Swain, 1974:12, pl. 9: fig. 16 [in part].

DIMENSIONS.—The illustrated female right valve is 1010 microns long and 610 high.

AGE RANGE.—Pliocene to Holocene.

DISTRIBUTION.—Chesapeake Bay to Laguna Terminos, Mexico, Puerto Rico, and the Bahamas in the Holocene, primarily in estuaries and lagoons. Pleistocene to Holocene, Virginia–North Carolina region; Pliocene to Holocene in Florida. In the present study, the species is known only by one valve from sample 15 in the Croatan Formation.

## *Peratocytheridea sandbergi*, new species

PLATE 4: FIGURES 1, 2, 3

*Haplocytheridea bassleri* (Stephenson).—Pooser, 1965:43, pl. 3: figs. 4–9.

*Haplocytheridea setipunctata* (Brady).—Swain, 1968:7, pl. 1: figs. 5a–c; pl. 7: figs. 1a, b; 1974:12, pl. 9: fig. 16 [in part].

"*Haplocytheridea*" sp. B.—Hazel, 1971a:6, table 1, species 72.

*Peratocytheridea sandbergi* Hazel, 1977, figs. 3, 7h, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from the closely related *Peratocytheridea setipunctata* by its smaller size, subtle differences in arrangement of normal pores, and shape of the opaque areas of the valves as seen in transmitted light; normal pores of *P. sandbergi* are circular in outline whereas a mixture of circular and elongated pores is found in *P. setipunctata.* The smallest specimens of *P setipunctata* known to the writer occur in upper Pleistocene deposits in North Carolina and Virginia. The females in these samples average about 962 microns in length and the males 1038 microns. Both sexes of the living and fossil *P. setipunctata* from Florida are consistently longer than 1000 microns. *Peratocytheridea sandbergi* females from the *Pterygocythereis inexpectata* assemblage zone and the higher *Orionina vaughani* assemblage zone of the Yorktown Formation average 852 microns in length; males are the same length. In the Croatan Formation, *P. sandbergi* females are about the same size, but the males are somewhat smaller (about 781 microns). The anterodorsal angle in *P. sandbergi* is less acute in both females and males than in *P. setipunctata.*

HOLOTYPE.—A female left valve (Plate 4: figure 1), USNM, 172663, from the Yorktown Formation (sample 4).

ENTYMOLOGY:—Named in honor of P.A. Sandberg, University of Illinois.

DIMENSIONS (in microns).—Pooled data; there are some changes in dimension in the males through time; see above.

| | Female | | Male | |
|---|---|---|---|---|
| | Length | Height | Length | Height |
| N | 10 | 10 | 9 | 9 |
| M | 844 | 535 | 811 | 457 |
| sd | 24 | 24 | 41 | 31 |
| OR | 812–875 | 488–562 | 750–850 | 412–488 |
| V | 2.8 | 4.5 | 5.1 | 6.7 |

AGE RANGE.—Early Pliocene to Pleistocene.

DISTRIBUTION.—Upper *Pterygocythereis inexpectata* assemblage zone through *Puriana mesacostalis* assemblage zone in Virginia and North Carolina. Waccamaw and Duplin formations in South Carolina.

## Genus *Actinocythereis* Puri, 1953

TYPE SPECIES.—*Cythere exanthemata* Ulrich and Bassler, 1904.

### *Actinocythereis captionis*, new species

PLATE 8: FIGURES 1, 2, 4

*Cythereis exanthemata* var. *gomillionensis* Howe and Ellis.—Edwards, 1944:521, figs. 31, 32.

*Actinocythereis exanthemata.*—Puri, 1953a:179, pl. 2: figs. 4, 6; 1953b:252, pl. 13: fig. 7.—Hulings, 1966:55, fig. 8h; 1967:655, fig. 7k.—Swain, 1968:14, fig. 12, pl. 2: fig. 5a–f. [Not *Cythere exanthemata* Ulrich and Bassler.]

*Actinocythereis exanthemata gomillionensis* (Howe and Ellis).—McLean, 1957:83, pl. 10: figs. 2a-d.—Swain, 1974:31, pl. 4: fig. 22.

*Actinocythereis gomillionensis* (Howe and Ellis).—Williams, 1966:30, figs. 6a–c, 24.

*Actinocythereis* sp. B.—Hazel, 1971a:6, table 1, species 42.

*Actinocythereis* aff. *A. gomillionensis* (Howe and Ellis).—Valentine, 1971, pl. 1: figs. 39, 40, 44, 48.

*Actinocythereis exanthemata exanthemata* (Ulrich and Bassler).—Swain, 1974:30, [partim], pl. 5: fig. 2.

*Actinocythereis captionis* Hazel, 1977:379, figs. 3, 8c, table 1 [nomen nudum].—Cronin and Hazel, 1980:18, figs. 6g, h [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Actinocythereis exanthemata* (Ulrich and Bassler, 1904) by its smaller size, characteristic arrangement of bullate tubercles of the ventral and median rows, higher and more evenly rounded posterior, and smoother surface between tubercles. Distinguished from *A. gomillionensis* (Howe and Ellis, 1935) by its smaller size, different arrangement of bullate tubercles in the ventral row, less inflated carapace, and ornamental details of the muscle node. The posterior bullate tubercles of the ventral and median rows in *A. captionis* are set close together and at nearly the same angle, whereas in *A. gomillionensis* they are more *en echelon*.

HOLOTYPE.—A female carapace (Plate 8: figure 1), USNM 172461, from the Holocene Carolinian faunal province off Cape Fear, Holocene sample 2251; lat. 33°42.7′ N, long. 78°45.0′ W, 12 m depth.

ETYMOLOGY.—Latin, *captio*, deception.

DIMENSIONS.—The holotype measures 750 × 400 microns.

AGE RANGE.—Early Pliocene to Holocene.

DISTRIBUTION.—Cape Cod to Florida in the Holocene, common constituent of inner sublittoral Pliocene and Pleistocene assemblages of the Atlantic Coastal Plain from Delaware to Florida. *Actinocythereis captionis* is a mild-temperate to subtropical species.

## Genus *Neocaudites* Puri, 1960

TYPE SPECIES.—*Neocaudites nevianii* Puri, 1960 (=male of *N. triplistriatus* (Edwards, 1944).

### *Neocaudites variabilus*, new species

PLATE 5: FIGURES 1–3; PLATE 7: FIGURE 1

*Trachyleberis?* cf. *T.? triplistriata* (Edwards).—Swain, 1951:37, pl. 6: figs. 2, 3.

*Orionina lienenklausi* (Ulrich and Bassler).—Puri, 1953b:254, fig. 8d, pl. 12: fig. 14.

*Costa* sp., aff. *C. triplistriata.*—Hall, 1965:33, pl. 7: fig. 8.

*Neocaudites* sp. A.—Valentine, 1971, pl. 3: figs. 38, 42.

*Neocaudites variabilis* Hazel.—Cronin and Hazel, 1980:23, fig. 8h [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Larger, more produced at the posterior, and with a less well-developed ventrolateral carina than *Neocaudites triplistriatus* (Edwards, 1944); surface may vary from nearly smooth to coarsely reticulate, whereas *N. triplistriatus* never has a well-developed reticulum. Distinguished from *Neocaudites subimpressus* (Edwards, 1944) by its larger size, more produced posterior, and absence of the concentric rows of large fossae paralleling the anterior.

HOLOTYPE.—Female right valve (Plate 7: figure 1), USNM 190494, from the Duplin Formation near Magnolia, North Carolina, USGS 23639.

ETYMOLOGY.—Latin, *variabilus*, changeable;

with reference to the variation of the reticulum.

DIMENSIONS.—The holotype measures 650 × 338 microns; a female right valve measures 663 × 338 microns; a male paratype measures 725 × 375 microns.

AGE RANGE.—Pliocene to Holocene.

DISTRIBUTION.—Yorktown, Duplin, Norfolk, Waccamaw formations (Pliocene and Pleistocene) in the North Carolina–Virginia region; Jackson Bluff Formation (Pliocene) in Florida. In the Holocene, the species has been found in 6 samples off North and South Carolina.

REMARKS.—The range of variation in this form is great and more than one species group taxon may well be present in what is here referred to *Neocaudites variabilus*. However, specimens are not common in any one sample, and more material will be required to determine whether there are consistently different morphotypes present and what is their stratigraphic and geographic distribution.

### *Neocaudites angulatus*, new species

PLATE 6: FIGURES 2–4

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Neocaudites triplistriatus* (Edwards, 1944) by its larger size, more prominent ventrolateral carina, and by presence of a few large fossae rather than several small ones at the posterodorsal termination of the median carina.

HOLOTYPE.—Female carapace (Plate 6: figure 4), USNM 172742, from the Waccamaw Formation at Old Dock, North Carolina (locality NC-4 of Swain, 1968).

ETYMOLOGY.—Latin, *angulatus*, with angles; with reference to the pronounced ventrolateral carina, which in end view gives the carapace a more angulate form than is seen in other species.

DIMENSIONS.—The holotype measures 675 × 375 microns; the illustrated right valve measures 725 × 362 microns.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—Yorktown, Croatan, Duplin, and Waccamaw formations in North Carolina; it is not common in any sample.

## Genus *Pterygocythereis* Blake, 1933

TYPE SPECIES.—*Cythereis jonesii* Baird, 1850

### *Pterygocythereis alophia*, new species

PLATE 7: FIGURES 2, 4

*Pterygocythereis cornuta americana*.—Puri, 1953b:261 [partim], pl. 13: figs. 2, 4

*Pterygocythereis* sp., aff. *P. americana*.—Benson and Coleman, 1963:22, pl. 5: figs. 2, 3 [partim].—Swain, 1968:19, fig. 18, pl. 2: figs. 7a–d.

*Pterygocythereis* sp., cf. *P. howei*.—Hulings, 1967:641, figs. 2f, 3m.

*Pterygocythereis* sp. A.—Valentine, 1971:8.

DIFFERENTIAL DIAGNOSIS.—Distinguished easily from *Pterygocythereis inexpectata* by its smaller size and absence of fluted crests. Distinguished from *P. miocenica* by its smaller size, less sloping dorsal outline, and position, size, and shape of the tab on the posterior of the ala; in *P. alophia*, this structure is small and is a blunt spine, whereas in *P. miocenica* it is a broad thin tab.

HOLOTYPE.—Female right valve (Plate 7: figure 4), USNM 172642, from Holocene sample 1861 in Raleigh Bay off North Carolina, lat. 34°45.6′ N, long. 75°44.6′ W, at 41 m depth.

ETYMOLOGY.—Greek, *lophos*, crest, with the negative prefix *a* with reference to the absence of a crest.

DIMENSIONS.—The holotype is 780 microns long and 415 high.

AGE RANGE.—Early Pliocene to Holocene.

DISTRIBUTION.—*Orionina vaughani* and *Puriana mesacostalis* assemblage zones in North Carolina, Bear Bluff Formation of DuBar et al. (1974:156), and Waccamaw Formation in the Carolinas, Jackson Bluff Formation in west Florida, and Tamiami Formation and "Pinecrest" beds of Olsson (1964) in south Florida. From off Virginia to at least off southwestern Florida in the Holocene.

REMARKS.—Van den Bold (1967) separated the uncrested Miocene and younger Coastal Plain and Caribbean species of *Pterygocythereis* from the crested *Pterygocythereis americana–P inexpectata* lineage, referring the former to his *P. miocenica*. All the Pliocene and younger uncrested specimens

seem to belong to one species, *P. alophia*, whereas the upper and middle Miocene forms belong to *P. miocenica*.

### Genus *Malzella*, new genus

*Malzella* Hazel, 1977:376, 379; figs. 3, 6c, d; table 1 [nomen nudum].

TYPE SPECIES.—*Malzella evexa*, new species.

DIFFERENTIAL DIAGNOSIS.—Dorsal precaudal ridge much better developed than in *Radimella* and continuous with the posterior subdorsal ridge. Dorsal ridge, which forms dorsal outline in lateral view, divided into anterior and posterior parts by intersection with short ridge homologous with dorsal end of anterosubdorsal ridge of *Radimella*. Carapace more evenly rounded dorsally and ventrally than in *Radimella*. Internal features as in *Radimella* except that posterior tooth is divided into 2 to 5 lobes. Surface more costate and more coarsely pitted than in *Aurila*; denticulate caudal process consistently present in *Malzella*, variably so in *Aurila*. Size within species quite variable, coefficients of variation near 7.0 common in populations.

REMARKS.—The following species are considered to be representatives of *Malzella*:

"*Aurila*" *bellegladensis* Kontrovitz, 1978; Pleistocene.

*Hemicythere conradi* Howe and McGuirt, 1935; late Miocene to Pliocene.

*Malzella evexa*, new species; Pliocene to early Pleistocene.

*Aurila floridana* Benson and Coleman, 1963, Pleistocene to Holocene.

*Aurila conradi littorala* Grossman, 1965; Holocene.

"*Aurila*", new species aff. *A. conradi* (Howe and McGuirt, 1935) of Howe and van den Bold (1975); early Holocene.

*Malzella* is a common constituent of Pliocene, Pleistocene, and Holocene deposits of the middle and southern Atlantic Coast and the Gulf Coast. As a fossil, at least, it extended to Venezuela (*Aurila conradi conradi* of Rodríguez, 1969). The oldest species known is *Malzella conradi* (Howe and McGuirt, 1935), which occurs in rocks as old as late Miocene (Red Bay Formation of Puri and Vernon, 1964, in Florida). Although most commonly found in modern and fossil marine shelf deposits, some species tolerate brackish and hypersaline conditions.

ETYMOLOGY.—*Malzella* is named in honor of Dr. Heinz Malz of the Senckenberg Museum, Frankfurt am Main, Germany.

### *Malzella evexa*, new species

PLATE 14: FIGURE 3; PLATE 15: FIGURES 1–3, 5

*Hemicythere conradi*.—Edwards, 1944:518, pl. 86: figs. 17, 18.—Swain, 1951:42, pl. 6: figs. 9–12.—Puri, 1953:176, pl. 2: figs. 1, 2.—Brown, 1958:65, pl. 6: fig. 17. [Not *Hemicythere conradi* Howe and McGuirt, 1935.]

*Aurila conradi conradi* (Howe and McGuirt).—Pooser, 1965:48, pl. 17: figs. 1, 2, 12, 13.—Swain, 1968:23, pl. 5: figs. 7a–i.

*Radimella floridana* (Benson and Coleman).—Hazel, 1971a:6, table 1, species 9.

*Malzella evexa* Hazel, 1977:376, 379, figs. 3, 6d, table 1 [nomen nudum].—Cronin and Hazel, 1980:15, fig. 4g [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Malzella conradi* by its more evenly rounded dorsum, more posteroventrally expanded ventrolateral carina, and by details of the arrangement of pores and fossae; distinguished from *M. floridana* by its smaller fossae and wider muri and less expanded ventrolateral carina.

HOLOTYPE.—Female left valve (plate 14: figure 3), USNM 172653, from the *Puriana mesacostalis* assemblage zone of the "Yorktown" near Mt. Gould Landing on the Chowan River, North Carolina, USGS 24897 (sample 20 of Hazel, 1971a).

ETYMOLOGY.—Latin, *evexus*, rounded at the top.

DIMENSIONS.—The holotype measures 738 × 475 microns; the illustrated male left valve measures 675 × 400 microns.

AGE RANGE.—Early Pliocene to early Pleistocene.

DISTRIBUTION.—Yorktown and Croatan formations in North Carolina; Bear Bluff of DuBar et al. (1974), Duplin, and Waccamaw formations in North and South Carolina; "Pinecrest" beds

of Olsson (1964) and Jackson Bluff, Tamiami, Caloosahatchee, and Bermont (of DuBar, 1974) formations in Florida.

REMARKS.—Most of the fossil specimens of *Malzella* from other than the Yorktown Formation referred to *M. conradi* are actually *M. evexa*; this apparently has resulted from most workers identifying *M. conradi* by use of Edwards' (1944, pl. 86, figs. 17, 18) illustrations of specimens that represent the early, smaller form of *M. evexa*.

*Malzella evexa* has not been found north of North Carolina. In table 1 of Hazel (1971a: 6), as the result of a clerical error, this taxon is indicated as occurring in sample 31, which is from the only known outcrop of the *Puriana mesacostalis* assemblage zone in Virginia. The species does not occur in sample 31. The calculations in the paper are not affected.

The specimens illustrated by Swain (1951:42; pl. 6, figs. 9–12) of *Hemicythere conradi* Howe and McGuirt are *Malzella evexa*; however, Swain's (1951:43) unillustrated specimens, USNM 560753 and 560760, represent *M. conradi* (Howe and McGuirt, 1935).

Populations of the species that have large females, such as the holotype, occur in *Puriana mesacostalis* assemblage zone deposits.

### Genus *Echinocythereis* Puri, 1953

TYPE SPECIES.—*Cythereis garretti* Howe and McGuirt, 1935.

### *Echinocythereis leecreekensis*, new species

PLATE 36: FIGURES 1–3, PLATE 38: FIGURE 3

*Buntonia?* cf. *B.? garretti*.—Swain, 1951:39 [partim], pl. 3: fig. 6.

*Echinocythereis evax*.—Brown, 1958:65, pl. 6: fig. 12.

*Echinocythereis garretti*.—Swain, 1968:15, fig. 13, pl. 4: fig. 12.

*Echinocythereis* sp. A.—Valentine, 1971:6, table 1.

*Echinocythereis leecreekensis* Hazel, 1977:378, figs. 3, 10h, table 1 [nomen nudum].—Cronin and Hazel, 1980:25, fig.. 9f [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—A large, very inflated species with an evenly rounded posterior and, on well-preserved specimens, a prominent posteroventral spine on each valve. Distinguished from *Echinocythereis margaritifera* by its larger size, more evenly rounded posterior, better developed posteroventral spine, and more obvious concentric arrangement of spines. Distinguished from *E. planibasalis* by its spinosity, lack of a reticulum, and absence of the ventrolateral alar-like row of spines present in *E. planibasalis*.

HOLOTYPE.—Female right valve (plate 36: figure 1), USNM 191495, Croatan Formation, USGS 25359 (sample 10).

DIMENSIONS.—The holotype measures 1013 microns in length and 650 in height; the illustrated female left valve measures 1000 × 675, and the illustrated male right valve, 1013 × 575 microns.

AGE RANGE.—Late Pliocene to Holocene.

DISTRIBUTION.—Croatan Formation (*Puriana mesacostalis* assemblage zone) in North Carolina; Bear Bluff of DuBar et al. (1974) and Waccamaw formations in North and South Carolina; Pliocene deposits in cores taken offshore of Jacksonville, Florida. In the Holocene, seemingly conspecific specimens have been found off the Atlantic Coast from the southwest side of the Georges Bank to Florida.

### Genus *Caudites* Coryell and Fields, 1937

TYPE SPECIES.—*Caudites medialis* Coryell and Fields, 1937.

### *Caudites paraasymmetricus*, new species

PLATE 12: FIGURES 2–4

*Caudites sellardsi* (Howe and Neill).—Swain, 1968:22, pl. 6: figs. 2a, b.

*Caudites* sp.—Puri and Vanstrum, 1971, fig. 4.

*Caudites asymmetricus* Hazel, 1977:378, 380, figs. 3, 7f, table 1 [nomen nudum].

*Caudites paraasymmetricus* Hazel.—Cronin and Hazel, 1980:6–22, figs. 2, 8i; table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Caudites sellardsi* (Howe and Neill, 1935) by the asymmetry of the valves in which a well-developed vertically oriented carina, forming a right angle with the ventrolateral carinae, is present in the posterior area in the left valves but not in right valves where the ventrolateral carinae curve upward toward the posterodorsal area, and also

by the position of the short dorsolateral carina, which is positioned more dorsally in *C. paraasymmetricus* than in *C. sellardsi*. *Caudites paraasymmetricus* can be distinguished from *Caudites rectangularis* (Brady, 1869), which has a similar valve asymmetry, by the virtual absence of any median carina in the former. *Caudites paraasymmetricus* is very similar to *C. asymmetricus* Pokornyi (1970), but the caudal process is more centrally located than in the latter and the ventral carina extends farther toward the anterior.

Dimensions.—The holotype measures 650 × 325 microns; the illustrated female right valve measures 625 × 312 microns; the illustrated male right valve measures 588 × 300 microns.

Age Range.—Early Pleistocene.

Remarks.—In some 30 specimens of *Caudites paraasymmetricus* available for study, all the right valves possessed one type of ornamentation and the left valves another. A few of the relatively shorter and more elongated specimens are interpreted to be males; they possess the same valve asymmetry as those that must be the females.

Distribution.—Upper part of Croatan Formation and the Waccamaw Formation in North Carolina; Caloosahatchee Formation in Florida.

## Genus *Muellerina* Bassiouni, 1965

Type Species.—*Cythere latimarginata* Speyer, 1863.

### *Muellerina ohmerti*, new species

Plate 16: figure 3

*Trachyleberis? martini* (Ulrich and Bassler).—Swain, 1951:29, pl. 3: figs. 8, 15.

[?] *Trachyleberis* cf. *T.? micula* (Ulrich and Bassler).—Swain, 1951:29, fig. 3L.

*Trachyleberis martini* (Ulrich and Bassler).—Malkin, 1953:793, [partim], pl. 82: fig. 10.

*Murrayina martini* (Ulrich and Bassler).—Puri, 1953b:256, fig. 8e, f, pl. 12: figs. 11–13.—McLean, 1957:86, pl. 11: figs. 1a–c, 2a, b, 3a–d; 1966:68, pl. 22: fig. 2.

*Murrayina micula* (Ulrich and Bassler).—Williams, 1966:31, fig. 18-7, 25a, b.

*Murrayina canadensis* (Brady).—Hulings, 1966:55, figs. 4f–h, 8g; 1967:654, figs. 4n, 7h.

*Muellerina lienenklausi* (Ulrich and Bassler).—Hazel, 1967:21, pl. 3: figs. 3–6, 11; pl. 7: figs. 1, 4, 5, 7.—Swain, 1968:16 [partim], pl. 3: figs. 2a, b, ?c, e, f, ?g, h; 3a, c [not figs. 2d, 4a, = *Muellerina bassiounii*, new species; not figs. 3d, 4b, = *M. wardi*, new species; not fig. 3b, = a new species incompletely studied at present].—Hazel, 1968b:1266, table 1.

*Muellerina* aff. *M. lienenklausi* (Ulrich and Bassler).—Hazel, 1970, table 1.—Valentine, 1971, pl. 3: figs. 36, 40, table 1.

*Muellerina* sp. A.—Hazel, 1971a:6, table 1, species 28.

*Muellerina micula* (Ulrich and Bassler).—Swain, 1974:38, pl. 7: figs. 1, 3–8; ?pl. 7: fig. 2.

Differential Diagnosis.—Distinguished by its broad, evenly rounded anterior, acute anterodorsal angle, and relatively well-developed pair of carinae posterior to the muscle node. Slightly depressed area is located posterocentrally and contains several fossae; depression is open towards the anteroventral area, and a row of fossae extend from the depression to about midlength. *Muellerina ohmerti* is smaller, more quadrate, and more broadly rounded at the anterior than is *M. canadensis* (Brady, 1870). *Muellerina wardi*, new species also possesses a depression in the posterocentral area, but it is not open towards the anteroventral area. *Muellerina ohmerti* is also similar to *M. bassiounii*, new species, which also has a posterocentrally located area of fossae, but which is dissected by short carinae. Shape and distribution of surface fossae also are important in distinguishing *M. ohmerti* from other species. In the anterior part, particularly, the fossae of *M. ohmerti* tend to be circular in outline and discrete. In *M. bassiounii* and *M. wardi*, many of the homologous fossae are coalesced, and others are elongated.

Some of the soft parts of *M. ohmerti* have been illustrated (as *M. lienenklausi*) by Hazel (1967; pl. 7, figs. 1, 4, 5, 7).

Holotype.—Female left valve (Plate 16: figure 3), USNM 112741, from Holocene (sample 1287 of Hazel, 1967, 1970; Valentine, 1971). This specimen was also illustrated by Hazel (1967, pl. 3: fig. 4).

Etymology.—Named in honor of Dr. Wolf Ohmert, the author of the Subfamily Coquimbinae.

Dimensions.—The means for length and height for 22 Holocene female specimens are 682 microns and 377 microns, respectively, with observed ranges of 600–725 and 350–400 microns. The means for length and height for 16 Holocene

male specimens are 648 microns and 330 microns, respectively, with observed ranges of 625–675 and 312–362 microns. See also Hazel (1967:21).

AGE RANGE.—Late Miocene (?) and Pliocene to Holocene.

REMARKS.—Prior to 1967, when the writer referred this species to *Muellerina lienenklausi* (Ulrich and Bassler, 1904), specimens of the taxon were being consistently assigned to another species in another family (*Murrayina martini* (Ulrich and Bassler, 1904)). However, although *M. lienenklausi* is undoubtedly congeneric, the type specimen is broken, and the Calvert Formation (lower and middle Miocene) has yielded specimens of more than one species of *Muellerina*. At the present time it cannot be determined with complete certainty which of the Calvert or younger forms is *M. lienenklausi*. Therefore, *M. ohmerti* is proposed for the species referred to by the writer as *M. lienenklausi* in 1967, and *Muellerina* sp. A in 1971.

The specimens of *Muellerina* illustrated by Swain (1968, Pl. 3) are all on a single hole microslide in the National Museum of Natural History. Four species are present on the slide. The queried identifications in the synonymy above result from not being able to determine in all cases which specimen represents which of Swain's illustrations.

DISTRIBUTION.—From the Gulf of Maine to Florida in the Holocene; Virginia to Florida in the Pliocene; Pleistocene in Virginia, North Carolina, and western Atlantic submarine canyons. Specimens possibly referable to *M. ohmerti* have been found in the upper Miocene so-called "St. Marys" Formation of Virginia.

### *Muellerina canadensis petersburgensis*, new subspecies

PLATE 16: FIGURE 2, PLATE 18: FIGURES 1, 3

[?] *Trachyleberis martini* (Ulrich and Bassler).—Malkin, 1953: 793 [partim], pl 82: fig. 11.

*Muellerina* aff. *M. canadensis* (Brady).—Hazel, 1971a:6, table 1, species 61.

*Muellerina canadensis petersburgensis* Hazel, 1977:376, figs. 3, 10b, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Muellerina blowi* by details of the reticulum, particularly in the posterocentral area. Fossae in the posterocentral area of the valve in *Muellerina canadensis petersburgensis* are arranged in distinct rows; in *Muellerina blowi*, the pits are more randomly arranged. *Muellerina canadensis petersburgensis* is consistently smaller than its descendant subspecies *M. canadensis canadensis*; otherwise, the two taxa are very similar, and no other consistent morphologic differences have been noted.

Fifteen female specimens of *Muellerina canadensis petersburgensis* have a mean length of 657 microns, whereas the mean length of 22 female specimens of *M. canadensis* is 764 microns (Hazel, 1967:22). The student's *t* computed in comparing the means is 8.77, with 35 degrees of freedom, a value significant at less than 0.001.

HOLOTYPE.—Female left valve (Plate 16: figure 2), USNM 167408, from the lower part of the *Orionina vaughani* assemblage zone in the Yorktown Formation at Petersburg, Virginia (sample 38 of Hazel, 1971a).

ETYMOLOGY.—From the city of Petersburg, Virginia.

DIMENSIONS (in microns).—

| | Female | | Male | |
|---|---|---|---|---|
| | Length | Height | Length | Height |
| N | 15 | 11 | 2 | 2 |
| M | 657 | 344 | | |
| sd | 34 | 14 | | |
| OR | 612–700 | 323–362 | 625–675 | 312–325 |
| V | 5.1 | 4.1 | | – |

AGE RANGE.—Late Miocene to Pliocene.

DISTRIBUTION.—Yorktown and Croatan formations in the *Pterygocythereis inexpectata*, *Orionina vaughani*, and lower part of the *Puriana mesacostalis* assemblage zones in Virginia and North Carolina. Upper Miocene so-called "St. Marys" Formation in Virginia.

### *Muellerina bassiounii*, new species

PLATE 16: FIGURES 1, 4, PLATE 18: FIGURE 6

*Muellerina lienenklausi* (Ulrich and Bassler).—Swain, 1968:16 [partim], pl 3: figs. 2d, 4a.

*Muellerina* sp. D.—Hazel, 1971a:6, table 1, species 7.

*Muellerina bassiounii* Hazel, 1977:378, figs. 3, 10d, table 1 [nomen nudum].—Cronin and Hazel, 1980:19, fig. 6e [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Posterocentral area dissected by 3 or 4 vertically oriented, sinuous carinae; in *M. wardi*, which is morphologically close to *M. bassiounii*, in the same area on the valves there is a spatulate fossa, narrowest dorsally and either open or closed dorsally by bordering carinae. In the lower anterocentral area in *M. bassiounii*, usually 2 fossae coalesce to form a T-shaped compound fossa or a C-shaped fossa open towards the posterior. *Muellerina bassiounii* is also smaller than *M. wardi.*

HOLOTYPE.—Female left valve (Plate 16: figure 4), USNM 167410, from the type locality of the Croatan Formation on the Neuse River, North Carolina.

ETYMOLOGY.—Named in honor of Mohamed el Amin Ahmed Bassiouni of Cairo, Egypt, the author of the genus *Muellerina.*

DIMENSIONS (in microns).—

| | Female | | Male | |
|---|---|---|---|---|
| | Length | Height | Length | Height |
| N | 16 | 16 | 5 | 5 |
| M | 642 | 330 | 602 | 295 |
| sd | 24 | 13 | 6 | 7 |
| OR | 588–675 | 312–350 | 600–612 | 288–300 |
| V | 3.8 | 3.9 | 0.9 | 2.32 |

AGE RANGE.—Late Pliocene to early Pleistocene.

DISTRIBUTION.—*Puriana mesacostalis* assemblage zone in the "Yorktown," Croatan, and Waccamaw formations in North Carolina.

## *Muellerina wardi*, new species

PLATE 17: FIGURES 2, 4; PLATE 18: FIGURES 4, 5

*Murrayina martini* (Ulrich and Bassler).—Brown, 1958:65, pl. 3: fig. 3.

*Muellerina lienenklausi* (Ulrich and Bassler).—Swain, 1968:16 [partim], pl 3: figs. 3d, 4b.

*Muellerina* sp. E.—Hazel, 1971a:6, table 1, species 17.

*Muellerina wardi* Hazel, 1977:376, figs. 3, 10a, table 1 [nomen nudum].—Cronin and Hazel, 1980:19, fig. 6c [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Muellerina bassiounii* by a rather well-defined spatulate fossa located posterocentrally that is either closed or open dorsally (the narrow end); there is either a short isolated carina in the center of the fossa or the carina may be connected with the carina forming the anterior border of the fossa. In *M. bassiounii*, there is no clearly defined fossa in this area of the valve, but several vertically oriented, sinuous carinae. *Muellerina wardi* is significantly larger than *M. bassiounii.*

HOLOTYPE.—Female left valve (Plate 17: figure 4), USNM 167409, from the *Puriana mesacostalis* assemblage zone in the "Yorktown" Formation near Mt. Gould Landing, North Carolina (sample 20 of Hazel, 1971a).

ETYMOLOGY.—Named for L.W. Ward, U.S. Geological Survey, who supplied material used in this study.

DIMENSIONS (in microns).—

| | Female | | Male | |
|---|---|---|---|---|
| | Length | Height | Length | Height |
| N | 16 | 16 | 2 | 2 |
| M | 683 | 338 | – | – |
| sd | 19 | 11 | – | – |
| OR | 650–725 | 325–350 | 625 | 288–300 |
| V | 2.7 | 3.3 | – | – |

AGE RANGE.—Pliocene to early Pleistocene.

OCCURRENCE.—*Orionina vaughani* and *Puriana mesacostalis* assemblage zones in Virginia and North Carolina. The species has been found in the Yorktown, Duplin, Croatan, Bear Bluff of DuBar et al. (1974), and Waccamaw formations in Virginia and the Carolinas, the "Pinecrest" beds of Olsson (1964) in south Florida, and Pliocene from cores offshore from Jacksonville, Florida.

## *Muellerina blowi*, new species

PLATE 17: FIGURES 1, 3; PLATE 18: FIGURE 2

*Muellerina* sp. F.—Hazel, 1971a:6, table 1, species 21.

*Muellerina blowi* Hazel, 1977:376, figs. 3, 10c, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Differs from *M. ohmerti*, *M. wardi*, and *M. bassiounii* in that the

valves are evenly convex in the posterocentral area with no large fossae or prominent carinae present. *Muellerina canadensis* (Brady, 1870) is similar in this respect, but the fossae of that species are aligned in distinct rows in the posterior, whereas in *M. blowi* there is only indistinct alignment of a few of the fossae. In *M. blowi*, fossae are relatively smaller and the intervening murae wider than in other *Muellerina* species. Sexual dimorphism is weak, and sexing of individual specimens is difficult.

HOLOTYPE.—Female left valve (Plate 17: figure 1), USNM 167411, from the *Orionina vaughani* assemblage zone of the Yorktown Formation at Suffolk, Virginia (sample 29 of Hazel, 1971a).

ETYMOLOGY.—Named for Warren Blow, formerly of the U.S. Geological Survey, who supplied valuable material and technical assistance during this study.

DIMENSIONS.—Assumed females range from 625 to 688 microns in length and 325 to 350 microns in height. The assumed males range from 588 to 650 microns in length and 275 to 312 microns in height.

AGE RANGE.—Pliocene to early Pleistocene.

OCCURRENCE.—*Pterygocythereis inexpectata*, *Orionina vaughani*, and *Puriana mesacostalis* assemblage zones in Virginia and North Carolina, Yorktown, "Yorktown," and Croatan formations.

## Genus *Thaerocythere* Hazel, 1967

TYPE SPECIES.—*Cythereis crenulata* Sars, 1865.

### *Thaerocythere carolinensis*, new species

PLATE 19: FIGURES 1, 3, 4

*Trachyleberis?*, cf. *T.? angulata* (Sars).—Swain, 1951:29, pl 3: figs. 9–12.

*Hemicythere schmidtae* Malkin.—Brown, 1958:66, pl 3: fig. 1.

*Thaerocythere* sp.—Swain, 1974:40, pl. 7: fig. 16.

*Thaerocythere carolinensis* Hazel, 1977:377, 378, figs. 3, 6f, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished by the presence of a low, wide, smooth tubercle located in the posterocentral area just behind and above the broad muscle tubercle; posterior termination of the dorsolateral carina is also marked by a large swelling, and another is present in the posterocentral area. In these characteristics, *T. carolinensis* differs from the related species *T. schmidtae* (Malkin, 1953) in which the surface is regularly pitted and there are no prominent tubercles other than the muscle tubercle.

HOLOTYPE.—Female carapace (Plate 19: figure 4), USNM 172657, from the *Puriana mesacostalis* assemblage zone in the "Yorktown" Formation at Colerain Landing, North Carolina (sample 14 of Hazel, 1971a).

DIMENSIONS (in microns).—The data are pooled; the holotype measures 750 × 450 microns.

| | Female | | Male | |
|---|---|---|---|---|
| | Length | Height | Length | Height |
| N | 10 | 10 | 4 | 4 |
| M | 735 | 446 | 679 | 409 |
| sd | 32 | 19 | 19 | 11 |
| OR | 700–800 | 425–488 | 675–712 | 400–425 |
| V | 4.3 | 4.4 | 2.7 | 2.9 |

AGE RANGE.—Late Pliocene to early Pleistocene.

DISTRIBUTION.—*Puriana mesacostalis* assemblage zone in the "Yorktown" Formation in the Chowan River area of North Carolina and the Croatan Formation at the Lee Creek Mine. Swain (1974:41) indicated that *Thaerocythere carolinensis* occurs in the type Yorktown Formation in Virginia (his sample S-5), referable to the *Orionina vaughani* assemblage zone. However, the writer has never seen this species in deposits of this age, and it is not present in the original material from collection S-5, which is in U.S. Geological Survey collections.

## Genus *Hermanites* Puri, 1955

TYPE SPECIES.—*Hermania reticulata* Puri, 1953.

### *Hermanites ascitus*, new species

PLATE 11: FIGURES 1–3

*Hermanites ascitus* Hazel, 1977, figs. 3, 6h, table 1 [nomen nudum].—Cronin and Hazel, 1980:19, fig. 6f [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Smaller than *Hermanites reticulatus* and with a less well-developed reticulum, which is nonfoveolate as compared with *H. recitulatus*; median carina traversing posterior half of valves also serves to distinguish the species; in *H. ascitus*, the ventrolateral carina is above the ventral outline in lateral view, whereas in *H. reticulatus*, this carina forms the ventral outline.

HOLOTYPE.—Female left valve (Plate 11: figure 1), USNM 172745, from the Duplin Formation on the left bank of the Lumber River, near Lumberton, North Carolina, 1.5 miles (2.4 km) south of intersection of routes 211 and 74. Sample taken 1 foot (0.3 m) below water level in gray shelly sand.

DIMENSIONS.—The holotype is 600 microns long and 350 microns high; the male left valve measures 550 × 288 microns and the female right valve 575 × 312 microns.

AGE RANGE.—Late Miocene to Pliocene.

DISTRIBUTION.—Known from samples 8 and 9 of the present study, the Duplin Formation of North Carolina near Lumberton and at the Robeson Farm near Tar Heel, Bear Bluff Formation of DuBar et al. (1974) near Bayboro, North Carolina, and the upper part of the so-called "St. Marys" Formation of Virginia.

## Genus *Puriana* Coryell and Fields, 1953

TYPE SPECIES.—*Favella puella* Coryell and Fields, 1937 (= *Cythereis rugipunctata* var. *gatunensis* Coryell and Fields, 1937).

### *Puriana carolinensis*, new species

PLATE 27: FIGURES 1, 3, 4

*Favella rugipunctata* (Ulrich and Bassler).—Malkin, 1953:79, pl. 82, fig. 24.

*Puriana mesicostalis* (Edwards) [sic].—Swain, 1968:19, pl. 5, fig. 13.

*Puriana* sp. D.—Hazel, 1971a:6, species 10 (add samples 5, 6, 7, and 19.

*Puriana carolinensis* Hazel, 1977:376, figs. 3, 8b, table 1 [nomen nudum].—Cronin and Hazel, 1980:15, fig. 4b [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Small, with a relatively strongly convex dorsum and concave venter. Arrangement of carinae and short tubercles on the surface is characteristic. Behind the muscle node is a carina oriented parallel to the length; the ridge may be whole or divided into two parts. Anterior to the muscle node are two intersecting carinae forming a Y. In some populations, the surface carinae in *P. carolinensis* are quite thick relative to the intercarinal areas. Sexual dimorphism indistinct; what are probably males are slightly smaller and slightly more elongated than females. A similar undescribed species is found in the Holocene off the Atlantic Coast, but that taxon is without the carina posterior to the muscle node, and although there is a homologous structure to the Y-shaped compound ridge, the "Y" form is lost; in addition, *P. carolinensis* does not possess undercut ridges in the posterior half of the valves as does the Holocene species. *Puriana mesacostalis* (Edwards, 1944) possesses a carina posterior to the muscle node also, but *P carolinensis* is much smaller and less quadrate.

HOLOTYPE.—A female right valve (Plate 27: figure 1), USNM 172469, from the "Yorktown" Formation near Mt. Gould Landing, North Carolina (sample 20 of Hazel, 1971a).

ETYMOLOGY.—From North Carolina.

DIMENSIONS (in microns).—

| | Female | | Male | |
|---|---|---|---|---|
| | Length | Height | Length | Height |
| N | 12 | 12 | 2 | 2 |
| M | 554 | 291 | – | – |
| sd | 18 | 11 | – | – |
| OR | 525–575 | 275–312 | 500–525 | 250–275 |
| V | 3.2 | 3.7 | – | |

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—*Pterygocythereis inexpectata*, *Orionina vaughani*, and *Puriana mesacostalis* assemblage zones; Yorktown, Croatan, Duplin, and Waccamaw formations in North Carolina; Bear Bluff of DuBar et al. (1974) and Waccamaw formations in South Carolina; *Cancellaria* and *Ecphora* zones of the Jackson Bluff Formation in western Florida; "Pinecrest" beds of Olsson (1964), and Tamiami Formation in southern Florida.

### Subfamily CAMPYLOCYTHERINAE Puri, 1960

In 1967, the writer considered the Campylocytherinae Puri, 1960, synonymous with the Leguminocythereididae Howe, 1961, at the subfamily level and placed this taxon in the Hemicytheridae. This is no longer believed to be correct. The Leguminocythereinae and Campylocytherinae are still believed to be closely related, but now the writer considers them as separate tribes within the subfamily Campylocytherinae.

The genera *Campylocythere* and *Acuticythereis*, both proposed by Edwards (1944), and *Proteoconcha* Plusquellec and Sandberg, 1969, were monographed by Plusquellec and Sandberg in a very useful paper. The reader is referred to Plusquellec and Sandberg (1969) for diagnoses and morphologic details of the Campylocytherini. These taxa, plus the less well understood southern forms of *Climacoidea* Puri, 1956, and *Reticulocythereis* Puri, 1960, constitute the North American Campylocytherini.

The genera *Leguminocythereis* Howe and Law, 1936, *Triginglymus* Blake, 1951, *Anticythereis* van den Bold, 1946, and *Bensonocythere* Hazel, 1967, constitute the Leguminocythereidini. The last genus is the only representative of the subfamily to occur in the middle Miocene to Holocene interval. *Bensonocythere* seems to be endemic to the Atlantic Coast of North America, where it is found in sediments deposited in cold-temperate to subtropical waters.

*Chrysocythere* Ruggieri, 1962, which was included with this general group by the writer in 1967 (p. 26), is actually a thaerocytherine, and *Basslerites* Howe, 1937, is perhaps a buntonid. *Leniocythere* Howe, 1951, which may be a senior synonym of *Pseudocytheromorpha* Puri, 1957, may belong to the Leguminocythereidini but is in need of more study.

### Genus *Proteoconcha* Plusquellec and Sandberg, 1969

TYPE SPECIES.—*Proteoconcha proteus* Plusquellec and Sandberg, 1969 (= *Acuticythereis nelsonensis* Grossman, 1967).

#### *Proteoconcha jamesensis*, new species

PLATE 25: FIGURES 1, 2; PLATE 27: FIGURE 2

*Proteoconcha* sp. E.—Hazel, 1971a:6, species 19.

DIFFERENTIAL DIAGNOSIS.—Higher relative to its length than most other species of *Proteoconcha*, except *P. gigantica* (Edwards, 1944), a larger and otherwise distinctive species. More tumid in the posteroventral area than other species of the genus. Males much less acuminate at the posterior than other species, except *P. gigantica* and *P. redbayensis* (Puri, 1953). Surface can be smooth or pitted, the pitting being mainly in the posterior half of the valves. Arrangement of normal pore canals (all sieve type) is most like that seen in *P. nelsonensis* (Grossman, 1967) but differs in detail.

HOLOTYPE.—Female left valve (Plate 25: figure 1), USNM 167377, in the *Orionina vaughani* assemblage zone of the Yorktown Formation, USGS 24622 (sample 32 of Hazel, 1971a).

ETYMOLOGY.—From the James River of Virginia.

DIMENSIONS.—The holotype is 700 microns long and 425 microns high.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—*Orionina vaughani* and *Puriana mesacostalis* assemblage zones in Virginia and North Carolina.

### Genus *Bensonocythere* Hazel, 1967

### (= *Prodictyocythere* Swain, 1974)

TYPE SPECIES.—*Leguminocythereis whitei* Swain, 1951.

REMARKS.—When this genus was proposed in 1967, the writer had no idea of its persistence in Miocene to Holocene Atlantic Coast deposits. In that paper, only the northern Holocene assemblages from the Atlantic shelf were studied, and only three species of *Bensonocythere* were recognized. At that time, Miocene, Pliocene, or Pleistocene Atlantic Coast assemblages had not been studied in any detail, and the same was true of Holocene assemblages south of New Jersey.

At least 17 species are present in the Pliocene

to Holocene deposits of the Middle Atlantic Coast. Other species, as yet not fully studied, are found in the middle and upper Miocene deposits. *Bensonocythere*, the coquimbine genus *Muellerina*, and the thaerocytherine *Puriana*, characterize and make distinctive the sublittoral fossil and living cold-temperate to subtropical assemblages of the western North Atlantic.

The word "persistence" was used above purposely, because often in contrast to *Muellerina* and *Puriana*, individual species of *Bensonocythere* seldom dominate an assemblage or even number among the abundant forms of it. However, in sublittoral marine to polyhaline assemblages several *Bensonocythere* species are commonly present.

Identification is not easy, as is also the case with the Campylocytherini. Size and shape are, of course, important; however, many species are similar in this respect. The normal pore-canal positions are one very diagnostic feature of *Bensonocythere* species; however, because most species have a coarse reticulum, the pores are not readily discernible at normal working magnifications in incident or transmitted light. Furthermore, the fossae on fossil and Holocene specimens often are filled with sediment. Fortunately the fossae themselves are covariant with the normal pores; thus, these can be homologized from specimen to specimen to delineate species. The height and width of the muri between the pits are variable, but the positions of these are also consistent among conspecific individuals.

The recently proposed genus *Prodictyocythere* (Swain, 1974), is, in this writer's opinion, a synonym of *Bensonocythere.*

### *Bensonocythere bradyi*, new species

PLATE 34: FIGURES 1, 2; PLATE 38, FIGURES 2, 4

*Bensonocythere* sp. R.—Hazel, 1971a, table 1, species 1.
*Bensonocythere bradyi* Hazel, 1977:376, figs. 3, 9g, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Bensonocythere ricespitensis* by its larger size and details of the reticulum; for example, the three coalescing fossae immediately anterior to the subcentral tubercle are not present or are ill defined in *B. ricespitensis*; the circular arrangement of pits just below the anterior to the subcentral tubercle is also different in *B. ricespitensis.* In size and shape, *B. bradyi* is similar to *B. gouldensis*, but the pattern of fossae is distinctly different.

HOLOTYPE.—Male right valve (Plate 34: figure 1), USNM 167380, from the *Puriana mesacostalis* assemblage zone on the Chowan River near Mount Gould Landing, North Carolina (sample 17 of Hazel, 1971a).

ETYMOLOGY.—Named for the 19th- and early 20th-century English ostracode worker, G.S. Brady.

DIMENSIONS.—The holotype is 850 microns long by 375 microns high; the illustrated male left valve measures 850 × 400 microns; the illustrated female right valve (interior view) measures 900 × 425 microns.

DISTRIBUTION.—Common in the *Orionina vaughani* and *Puriana mesacostalis* assemblage zones in Virginia and North Carolina and rare in the *Pterygocythereis inexpectata* assemblage zone.

REMARKS.—In the *Puriana mesacostalis* assemblage zone, specimens assigned to this species possess wider muri relative to the fossae than in populations from the older zones. Compare plates 34 and 38.

### *Bensonocythere blackwelderi*, new species

PLATE 35: FIGURES 1, 2, 4; PLATE 37: FIGURE 4

*Bensonocythere* sp. J.—Hazel, 1971a, table 1, species 75.
*Bensonocythere* sp. K.—Hazel, 1971a, table 1, species 17.
*Bensonocythere* sp. G.—Valentine, 1971, pl 1: fig. 23, table 1.

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Bensonocythere ricespitensis* by its more evenly rounded anterior and posterior; more convex (particularly in females) rather than straight dorsum; the arrangement of fossae and muri over the surface also distinguishes *B. blackwelderi* from *B. ricespitensis*, particularly that in the posterior half of the valves and in the anteroventral area. *Bensonocythere blackwelderi* is smaller than *B. bradyi*, and the arrangement of fossae is distinctly different.

HOLOTYPE.—Female left valve (Plate 35: figure

4), USNM 167398, from the *Orionina vaughani* assemblage zone in the Yorktown Formation in Virginia near Tormentor Creek, a tributary to the James River in Isle of Wight County, Virginia (sample 33 of Hazel, 1971a).

ETYMOLOGY.—Named in honor of B.W. Blackwelder, formerly of the U.S. Geological Survey.

DIMENSIONS.—The holotype is 781 microns long and 425 microns high.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—*Pterygocythereis inexpectata* (rare), *Orionina vaughani*, and *Puriana mesacostalis* assemblage zones in Virginia and North Carolina. The forms with particularly wide muri have been found only in the older two zones in the Yorktown Formation. The specimen illustrated by Valentine (1971) as *Bensonocythere* sp. G from upper Pleistocene deposits near Yadkin, Virginia, is probably a reworked *Orionina vaughani* assemblage zone form.

### *Bensonocythere gouldensis*, new species

Plate 34: FIGURES 3, 4; PLATE 37: FIGURES 2, 3

*Leguminocythereis whitei* Swain, 1951:43 [partim], pl. 3: fig. 18; pl. 4: fig. 1.—Brown, 1958:63, pl. 6: fig. 10.
*Bensonocythere* sp. B.—Hazel, 1971a, table 1, species 44.
*Bensonocythere gouldensis* Hazel, 1977:376, figs. 3, 4a, table 1 [nomen nudum].—Cronin and Hazel, 1980:17, fig. 5a [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from the closely related *Bensonocythere blackwelderi* by its less evenly rounded anterior and by the slightly different pattern of fossae, particularly in the posterior half of the valves. In *B. gouldensis*, the first interior carina paralleling the anterior valve margin is close to but distinctly inside the anterior and anteroventral outline, whereas in *B. blackwelderi*, this carina tends to form the outline; the muri are narrower in *B. gouldensis* than in *B. blackwelderi.*

HOLOTYPE.—Female left valve (Plate 37: figure 2), USNM 167385, from the *Puriana mesacostalis* assemblage zone of the "Yorktown" Formation on the Chowan River, North Carolina, near Mt. Gould Landing (sample 19 of Hazel, 1971a).

ETYMOLOGY.—From Mt. Gould, North Carolina.

DIMENSIONS.—The female holotype measures 758 × 375 microns. Females are relatively shorter but absolutely larger; the largest measured female is 875 microns long.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—Yorktown and Croatan formations in Virginia and North Carolina; Duplin Formation in North Carolina.

### *Bensonocythere ricespitensis*, new species

Plate 33

*Leguminocythereis whitei* Swain, 1951:43 [partim], pl. 3: fig. 16.
*Bensonocythere* sp. N.—Hazel, 1971a, table 1, species 79.
*Bensonocythere ricespitensis* Hazel, 1977:376, figs. 3, 4c, table 1 [nomen nudum].—Cronin and Hazel, 1980:17, fig. 5b [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Bensonocythere bradyi* by its smaller size and characteristic arrangement of fossae, particularly in the area below and slightly anterior to the muscle node where there is a circular pattern of about 6 fossae; three of these are in a row subparallel to the greatest valve length, the anterior fossae slightly higher than the posterior one; below these are 3 or 4 fossae in a semicircle, open dorsally. *Bensonocythere sapeloensis* (Hall, 1965) has a similar arrangement of fossae in this part of the valve, but *B. ricespitensis* is larger, and the fossae pattern in the posterior of the valves is quite different.

HOLOTYPE.—Female left valve (Plate 33: figure 1), USNM 167394, from the *Orionina vaughani* assemblage zone at Mr. William Rice's marl pit in the Yorktown Formation at Hampton, Virginia, USGS 24907 (sample 36 of Hazel, 1971a).

DIMENSIONS.—The female holotype measures 750 × 400 microns. Males are about the same length but not as high.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—*Orionina vaughani* and *Puriana mesacostalis* assemblage zones in Virginia and North Carolina in the Yorktown and Croatan

formations; Waccamaw Formation in North Carolina.

### *Bensonocythere rugosa*, new species

PLATE 32: FIGURES 3, 4; PLATE 37: FIGURE 1

*Bensonocythere* sp. I.—Hazel, 1971a, table 1, species 51.
*Bensonocythere rugosa* Hazel, 1977:376, 378, figs. 3, 4b, table 1 [nomen nudum].—Cronin and Hazel, 1980:17, fig. 5c [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Bensonocythere whitei* (Swain, 1951) by its concave dorsum, convex venter, more oblique anterior and details of the reticulum. Distinguished from a morphologically similar undescribed late Pliocene to Holocene species (*Bensonocythere* sp. M. of Hazel, 1971a), which does not occur at Lee Creek, by its larger size, weaker sexual dimorphism, and details of the reticulum, particularly in the posterior part of the valves where the fossae are difficult to homologize. In both *B. rugosa* and *Bensonocythere* sp. M. of Hazel (1971a), the fossae are developed mainly between major vertically oriented muri and separated by minor muri; in *B. rugosa*, these minor muri are more weakly developed.

HOLOTYPE.—Female left valve (Plate 32: figure 4), USNM 167382, from the *Orionina vaughani* assemblage zone of the Yorktown Formation at Petersburg, Virginia, USGS 24909 (sample 39 of Hazel, 1971a).

ETYMOLOGY.—Latin, *rugosus*, wrinkled.

DIMENSIONS.—The holotype measures 688 × 388 microns; the other illustrated female right valve measures 700 × 350 microns; the illustrated male right valve measures 675 × 325 microns.

AGE RANGE.—Pliocene.

DISTRIBUTION.—Yorktown Formation in Virginia and North Carolina; lower part of Croatan and Duplin formations in North Carolina; Bear Bluff Formation of DuBar et al. (1974) in North and South Carolina; Tamiami Formation in Florida.

## Genus *Cytheromorpha* Hirschmann, 1909

TYPE SPECIES.—*Cythere fuscata* Brady, 1869.

### *Cytheromorpha incisa*, new species

PLATE 21: FIGURES 1, 2; PLATE 23: FIGURES 5, 6

*Cytheromorpha* sp. D.—Hazel, 1971a:6, species 48.
*Cytheromorpha incisa* Hazel, 1977, figs. 3, 9a, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Cytheromorpha macroincisa* by its smaller size, strongly developed reticulum with large fossae, wider but slightly shorter posteroventral incised area, more elongate posterior hinge tooth, and details of normal pore arrangement; distinguished from *Cytheromorpha warneri* Howe by the presence of the posteroventral incised area, which is absent in *C. warneri warneri* Howe and Spurgeon, 1935, and only weakly developed in *C. warneri newportensis* Williams, 1966.

HOLOTYPE.—Female left valve (Plate 21: figure 1), USNM 172560, from the *Puriana mesacostalis* assemblage zone of the "Yorktown" Formation, near Mt. Gould Landing, North Carolina, USGS 24895 (sample 18 of Hazel, 1971a).

ETYMOLOGY.—Latin, *incisus*, cut into, with reference to the posteroventral incised area of the valves.

DIMENSIONS.—The female holotype measures 550 microns long and 300 microns high; the illustrated male measures 563 × 275 microns.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—Throughout the Yorktown and Croatan formations in Virginia and North Carolina.

### *Cytheromorpha macroincisa*, new species

PLATE 22: FIGURES 1–5

*Cytheromorpha macroincisa* Hazel, 1977:377, 378, figs. 3, 9c, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Cytheromorpha incisa* by its pitted rather than reticulate surface, by the more narrow but longer incised area in posterior part of the ventrolateral surface of the valves; and by details of normal pore arrangement. Distinguished from *C. suffolkensis* by its more broadly rounded posterior, different arrangement of punctae and small carinae,

and the different shape, placement, and angle of the incised area, which is set farther forward in *C. macroincisa.*

HOLOTYPE.—Female left valve (Plate 22: figure 1), USNM 172562, from the *Puriana mesacostalis* assemblage zone of the "Yorktown" Formation near Mt. Gould Landing, North Carolina, USGS 24895 (sample 18 of Hazel, 1971a).

ETYMOLOGY.—Latin, *macro* and *incisus*, long and cut, with reference to the narrow elongated incised area in the valves.

DIMENSIONS.—The holotype is 613 microns long and 325 microns high; the illustrated female right valve measures 600 × 312 microns.

AGE RANGE.—Pliocene.

DISTRIBUTION.—*Puriana mesacostalis* assemblage zone in North Carolina, with one possible occurrence in the *Orionina vaughani* assemblage zone on the Virginia Eastern Shore; "Yorktown" and Croatan formations on the Chowan River in North Carolina.

### *Cytheromorpha suffolkensis*, new species

PLATE 23: FIGURES 1–4

*Cytheromorpha* sp. C.—Hazel, 1971a:6, species 56.
*Cytheromorpha warneri* Howe and Spurgeon.—Swain, 1974 [partim], pl 4: fig. 2.
*Cytheromorpha suffolkensis* Hazel, 1977:376, figs. 3, 9d, table 1 [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Cytheromorpha macroincisa* by its smaller size, differently shaped and positioned incised area on ventrolateral surface, which is set farther to the posterior in *C. suffolkensis.* Surface punctae similar in size to *C. macroincisa*, but the arrangement of punctae and small carina at anterior and posterior is different. Easily distinguished from *C. incisa* by its punctate rather than reticulate surface.

HOLOTYPE.—Female left valve (Plate 23: figure 1), USNM 172551, from the *Orionina vaughani* assemblage zone of the Yorktown Formation at Suffolk, Virginia, USGS 24814 (sample 29 of Hazel, 1971a).

ETYMOLOGY.—From Suffolk, Virginia.

DIMENSIONS.—The holotype is 525 microns long and 275 microns high; the illustrated male right valve measures 550 × 288 microns.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—*Orionina vaughani* and *Puriana mesacostalis* assemblage zones in Virginia and North Carolina, Yorktown, "Yorktown" on the Chowan River, and Croatan formations.

## Genus *Microcytherura* Müller, 1894

## (= *Tetracytherura* Ruggieri, 1952)

TYPE SPECIES.—*Microcytherura nigrescens* Müller, 1894.

### *Microcytherura minuta*, new species

PLATE 31: FIGURES 1–3

*Microcytherura* sp. O.—Hazel, 1971a, table 1, species 84.
*Microcytherura minuta* Hazel, 1977:376, figs. 3, 5b, table 1 [nomen nudum].—Cronin and Hazel, 1980:21, fig. 7g [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Smaller than other known species of *Microcytherura*; evenly rounded at the anterior and posterior, whereas *M. expanda* is more obliquely rounded and expanded (or inflated) at the posterior; reticulum developed with very fine pits in the fossae, in contrast to *M. expanda*, *M. similis*, and *M. choctawhatcheensis*, which have larger pits in the fossae.

HOLOTYPE.—Female left valve (Plate 31: figure 3) USNM 172750, from the *Orionina vaughani* assemblage zone in the Yorktown Formation at Williamsburg, Virginia (sample 45 of Hazel, 1971a).

DIMENSIONS.—The holotype is 488 microns long and 375 high; the illustrated female right valve measures 525 × 262 microns; and the illustrated male left valve is 513 × 250 microns.

DISTRIBUTION.—Yorktown Formation, *Pterygocythereis inexpectata* (one record) and *Orionina vaughani* assemblage zones, in Virginia and North Carolina; "Yorktown" on the Chowan River, Croatan, and Duplin formations and *Puriana mesacostalis* assemblage zone in North Carolina.

### *Microcytherura expanda*, new species

PLATE 30: FIGURES 1–3

*Microcytherura expanda* Hazel, 1977:377, 378, figs. 3, 5c, table 1 [nomen nudum].—Cronin and Hazel, 1980:21, fig. 7f [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Microcytherura similis* by its inflated and broadly rounded posterior and better developed reticulum. The intensity of the development of the reticulum is similar in *M. choctawhatcheensis*, but *M. expanda* in general has fewer pits present in the fossae, the positions of the fossae are different, and the posterior is more broadly rounded and inflated. Larger than *M. minuta* and with a higher posterior and pits in the fossae.

HOLOTYPE.—Female left valve (Plate 30: figure 2), USNM 172752, from the "Yorktown" Formation on the Chowan River, North Carolina, near Mt. Gould Landing, USGS 24897 (sample 20 of Hazel, 1971a).

ETYMOLOGY.—Latin, *expando*, spread out.

DIMENSIONS.—The holotype is 575 microns long and 312 high; the illustrated male left valve measures 550 × 300 microns; the illustrated female right valve is 537 × 300 microns.

AGE RANGE.—Late Pliocene to early Pleistocene.

DISTRIBUTION.—"Yorktown" Formation on the Chowan River, North Carolina; Croatan and Waccamaw formations also in North Carolina.

## Genus *Hirschmannia* Elofson, 1941

TYPE SPECIES.—*Cythere viridis* Müller, 1785.

### *Hirschmannia? hespera*, new species

PLATE 20: FIGURES 1, 2; PLATE 21: FIGURES 3, 4

*Hirschmannia?* sp. B.—Hazel, 1971a:6, species 15.

DIFFERENTIAL DIAGNOSIS.—Easily distinguished from *Hirschmannia viridis* by its more elongated valves. Distinguished from *H.? quadrata* by the fact that it is relatively much higher at the anterior than the posterior; the surface is covered with small punctae, whereas the surface of *H.? quadrata* is covered with relatively large fossae with second-order reticulation separated by low muri.

HOLOTYPE.—Female left valve (Plate 20: figure 1), USNM 172575, from sample 14 of the present study.

ETYMOLOGY.—Latin, *hesperus*, western, with reference to this being a western Atlantic member of the genus.

DIMENSIONS.—The holotype is 475 microns long and 250 microns high; the illustrated female right valve (Plate 20: figure 2) measures 488 × 250 microns.

AGE RANGE.—Pliocene.

DISTRIBUTION.—*Orionina vaughani* and *Puriana mesacostalis* assemblage zones in Virginia and North Carolina, Yorktown, "Yorktown," and Croatan formations.

### *Hirschmannia? quadrata*, new species

PLATE 20: FIGURES 3, 4

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Hirschmannia? hespera* by its less tapered posterior, more inturned ventral margin when viewed internally, and presence of a surface ornamentation of fossae with secondary reticulation separated by lower muri. The last characteristic, coupled with a straighter ventral outline, distinguishes the species from *H. viridis*.

HOLOTYPE.—Female left valve (Plate 20: figure 3), USNM 172571, from *Puriana mesacostalis* assemblage zone of the "Yorktown" Formation near Yadkin, Virginia, USGS 24905 (sample 31 of Hazel, 1971a).

ETYMOLOGY.—Latin, *quadratus*, squared.

DIMENSIONS.—The holotype is 475 microns long and 250 microns high; the illustrated male right valve, USNM 172573, measures 488 × 250.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—*Orionina vaughani* and *Puriana mesacostalis* assemblage zones of Virginia and North Carolina, including the subsurface of the Virginia Eastern Shore.

### Genus *Paracytheridea* Müller, 1894

TYPE SPECIES.—*Paracytheridea depressa* Müller, 1894.

### *Paracytheridea cronini*, new species

PLATE 28: FIGURES 1, 2; PLATE 29: FIGURE 1

*Paracytheridea nodosa.*—Swain, 1951:51 [partim], pl. 3: fig. 22.
*Paracytheridea* sp. A.—Hazel, 1971a:6, table 1, species 40.
*Paracytheridea mucra.*—Swain, 1974:20, pl. 1: fig. 23.
*Paracytheridea edwardsi* Hazel, 1977:376, figs. 3, 7a, table 1 [nomen nudum].—Cronin and Hazel, 1980:23, fig. 8d [nomen nudum].

DIFFERENTIAL DIAGNOSIS.—Distinguished from *Paracytheridea mucra* Edwards, 1944, by its smaller size, narrower posterior, better developed reticulum, and much less well-developed ala. Distinguished from *P. altila* Edwards, 1944, by its less pointed posterior, narrower muri, presence of a weakly developed sulcus, more broadly rounded anterior, and position of and trend of various carinae. Distinguished from *P. rugosa* by its less well-developed reticulum, more rounded posterior, and position of and more weakly developed carinae.

HOLOTYPE.—Female left valve (Plate 29: figure 1), USNM 172759, from the type locality of the Duplin Formation at Natural Well near Magnolia, North Carolina, USGS 23639. (See Edwards, 1944.)

ETYMOLOGY.—Named in honor of T.M. Cronin, U.S. Geological Survey.

DIMENSIONS.—The holotype is 575 microns long and 300 microns high.

AGE RANGE.—Pliocene to early Pleistocene.

DISTRIBUTION.—Yorktown Formation in Virginia and North Carolina, Duplin and Croatan formations in North Carolina, Bear Bluff Formation of DuBar et al. (1974) in South Carolina.

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Plates 1–38

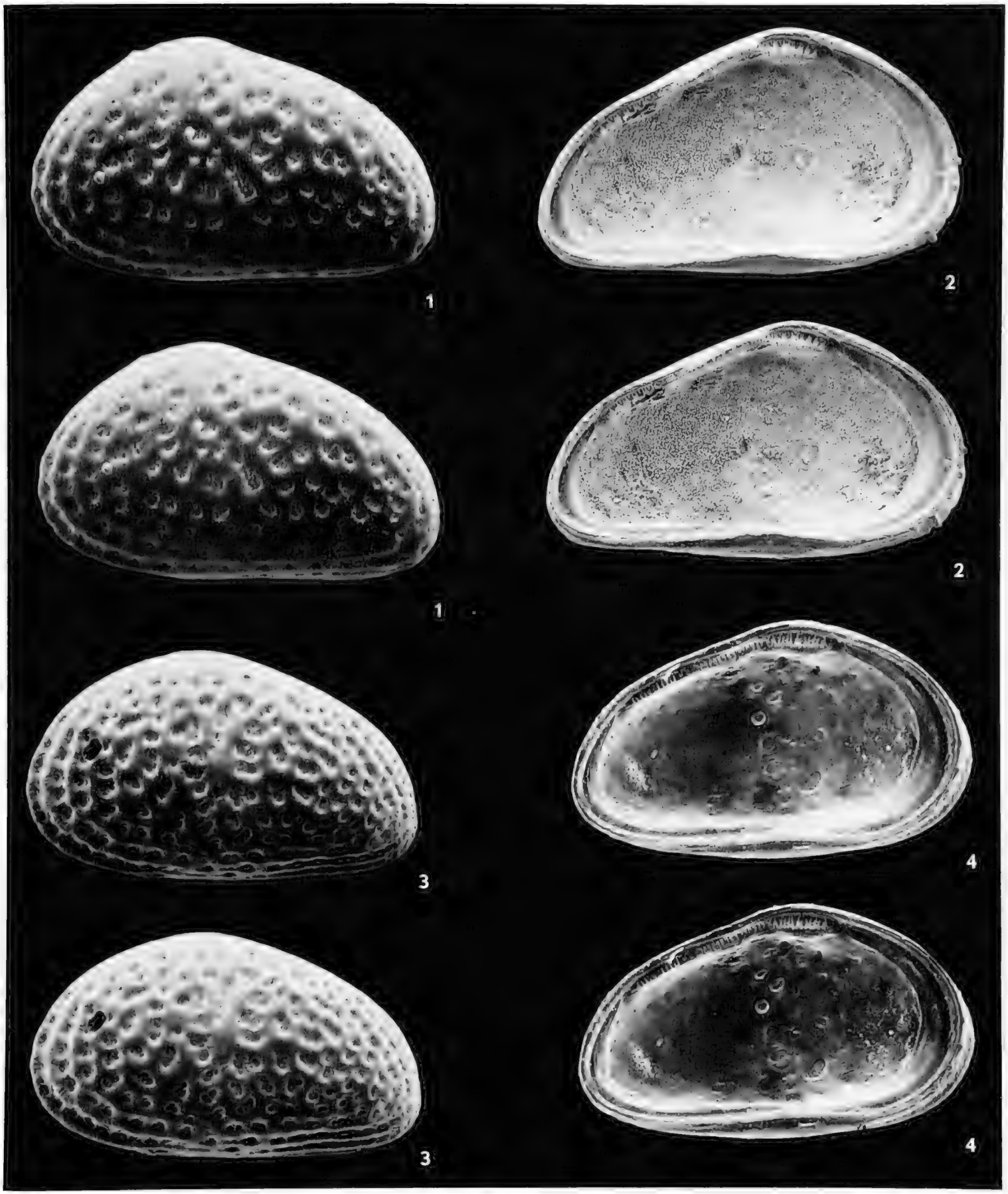
## PLATE 1

*Cytheridea* aff. *C. virginiensis* (Malkin, 1953)

1. Exterior view female left valve, USNM 172518, Yorktown Formation, sample 6 of this study, USGS 24883, × 81.
2. Interior view female left valve, USNM 313688, Yorktown Formation, James City County, Virginia, sample 42 of Hazel (1971a), USGS 24912, × 82.

*Cytheridea virginiensis* (Malkin, 1953)

3. Exterior view female left valve, USNM 172519, Yorktown Formation, Greenville County, Virginia, sample 27 of Hazel (1971a), USGS 24830, × 93.
4. Interior view female left valve, USNM 172511, Yorktown Formation, James City County, Virginia, sample VA-7 of Malkin (1953, pl. 79: fig. 30), × 93.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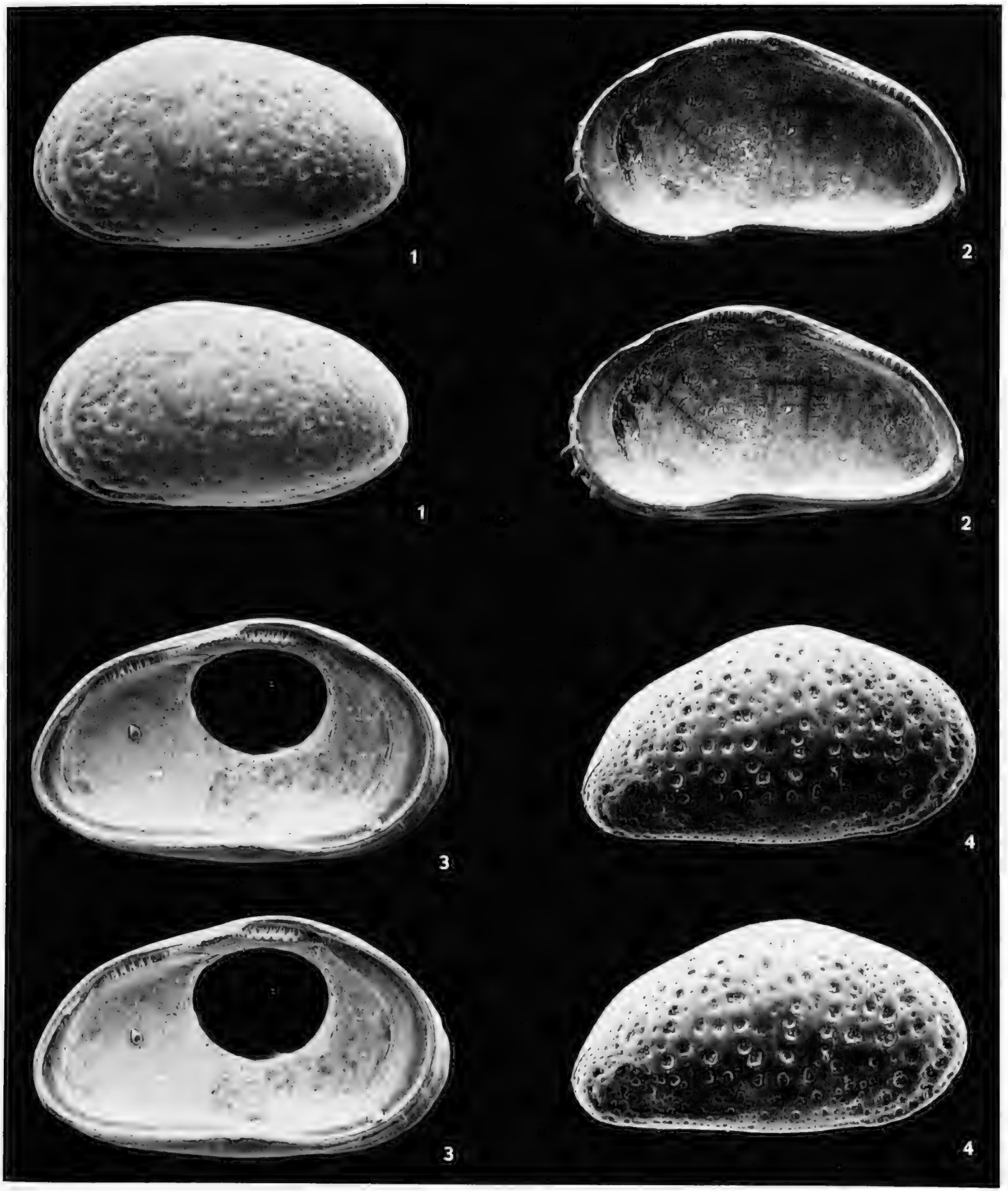
## PLATE 2

*Cytheridea campwallacensis*, new species

1. Exterior view male left valve, USNM 172506, Yorktown Formation, James City County, Virginia, sample 42 of Hazel (1971a), USGS 24912, × 75.
3. Interior view female left valve, USNM 191351, Yorktown Formation, Greenville County, Virginia, sample 27 of Hazel (1971a), USGS 24830, × 90.
4. Exterior view female right valve, holotype, USNM 172619, Yorktown Formation, James City County, Virginia, sample VA-7 of Malkin (1953, pl. 79: fig. 29), × 83.

*Cytheridea virginiensis* (Malkin, 1953)

2. Interior view female right valve, small form, USNM 191358, Croatan Formation, sample 15 of this study, USGS 25378, × 98.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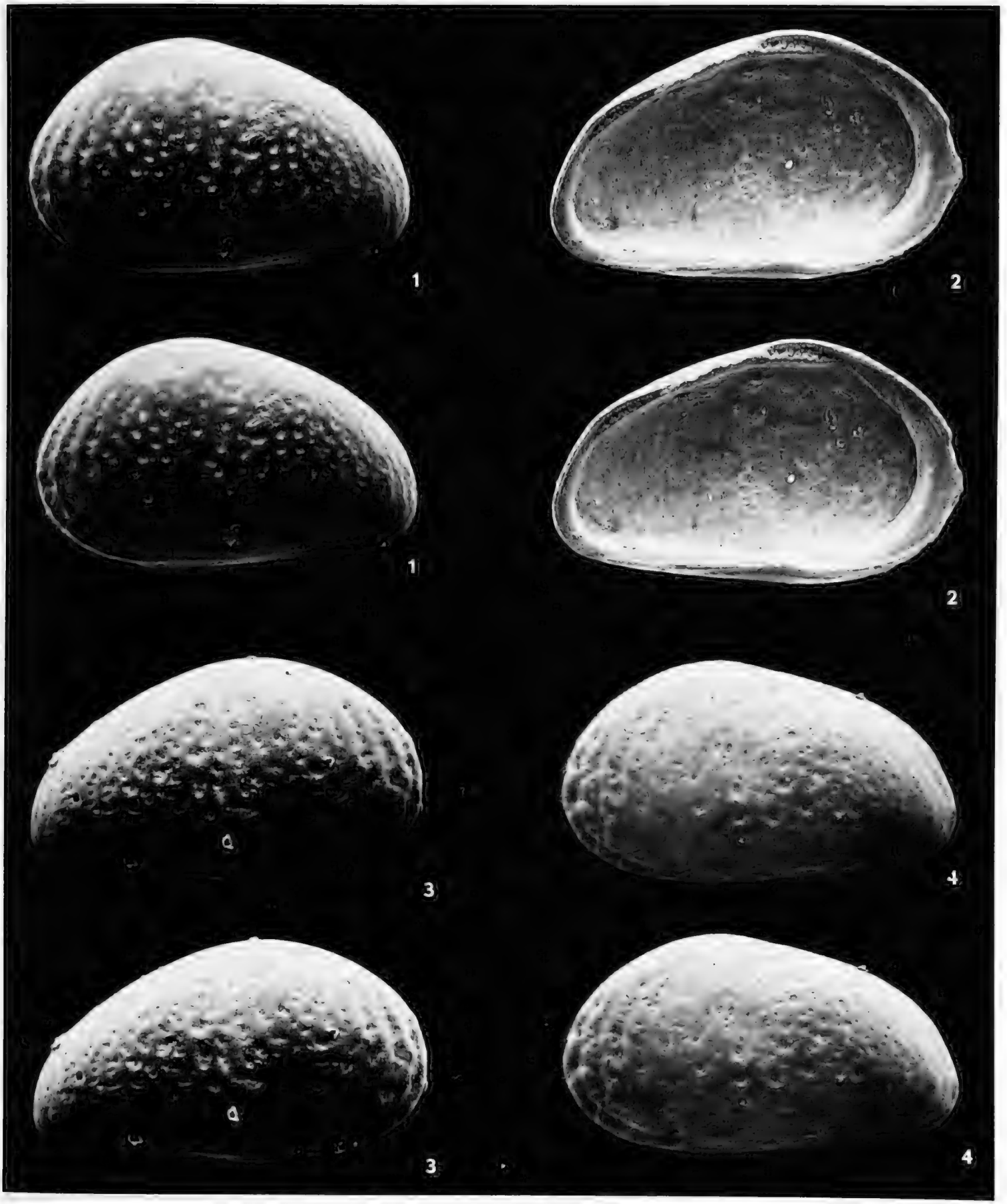
## PLATE 3

*Cytheridea carolinensis*, new species

1. Exterior view female left valve, USNM 191357, Croatan Formation, sample 15 of this study, USGS 25378, × 106.
2. Interior view female left valve, USNM 191337, Croatan Formation, sample 13 of this study, USGS 25377, × 114.
3. Exterior view female right valve, USNM 191359, "Yorktown" Formation near Colerain, North Carolina, sample 15 of Hazel (1971a), USGS 24892, × 106.
4. Exterior view male left valve, holotype, USNM 172509, Croatan Formation, sample 12 of this study, USGS 24886, × 105.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## PLATE 4

*Peratocytheridea sandbergi*, new species

1. Exterior view female left valve, holotype, USNM 172663, Yorktown Formation, sample 4 of this study, USGS 24881, × 87.
2. Interior view male right valve, USNM 172662, Yorktown Formation, sample 4 of this study, USGS 24881, × 87.
3. Exterior view male left valve, USNM 172661, Yorktown Formation, sample 6 of this study, USGS 24883, × 87.

*Peratocytheridea setipunctata* (Brady, 1869)

4. Exterior view female right valve, USNM 191504, Croatan Formation, sample 15 of this study, USGS 25378, × 74.

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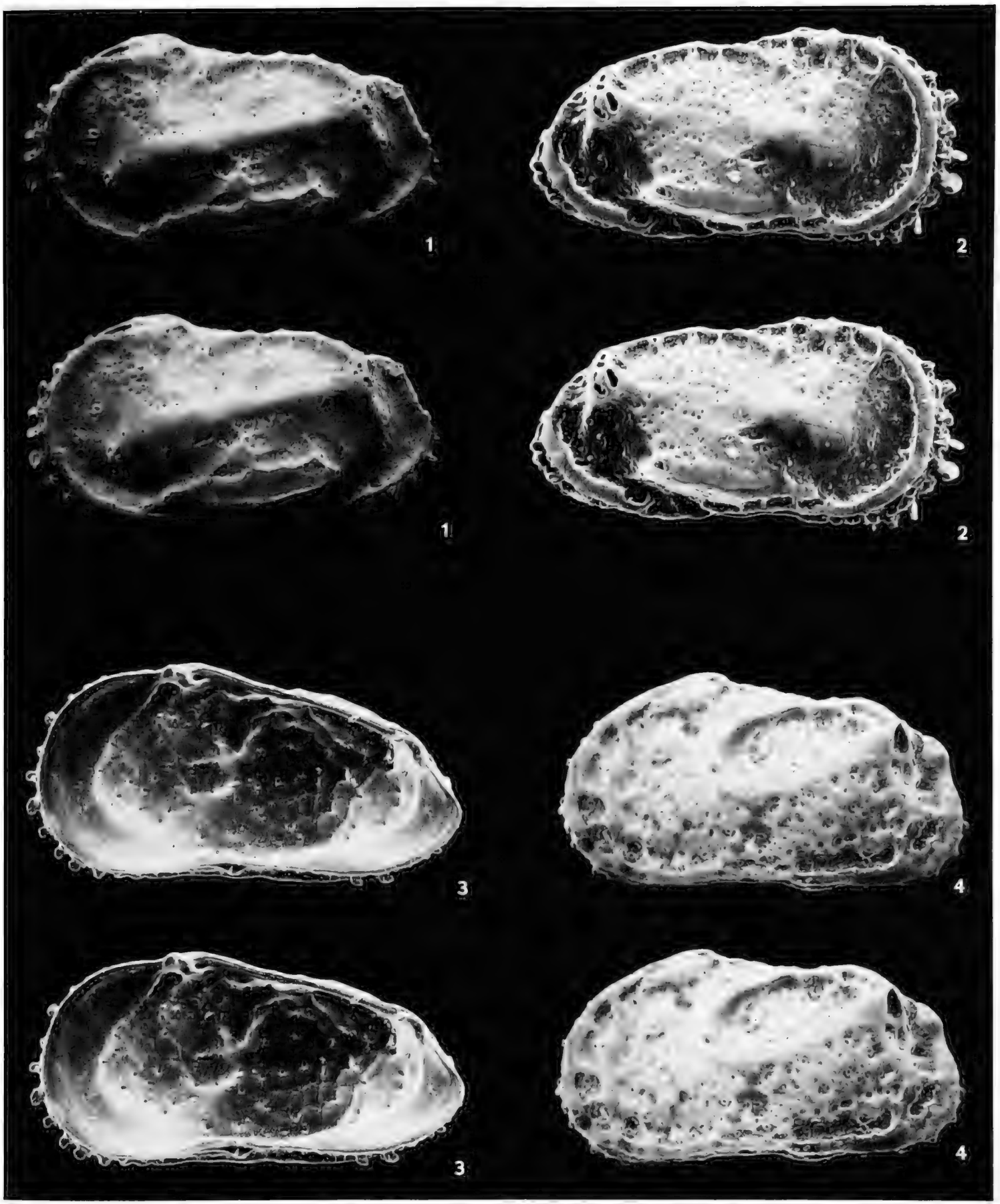
## PLATE 5

*Neocaudites variabilus*, new species

1. Exterior view male left valve, USNM 172745, Norfolk Formation (upper Pleistocene) at Virginia Beach, Virginia, locality P2-1 of Valentine (1971), USGS 23787, × 98.
2. Exterior view female right valve, USNM 191387, Yorktown Formation, Hampton City, Virginia, sample 34 of Hazel (1971a), USGS 24810, × 110.
3. Interior view female right valve, USNM 191386, type locality of the Duplin Formation near Magnolia, North Carolina, USGS 23639, × 120.

*Neocaudites subimpressus* (Edwards, 1944)

4. Exterior view female left valve, USNM 559432, Duplin Formation, near Lumberton, North Carolina, locality 3 of Edwards (1944, pl. 87: fig. 30), × 109.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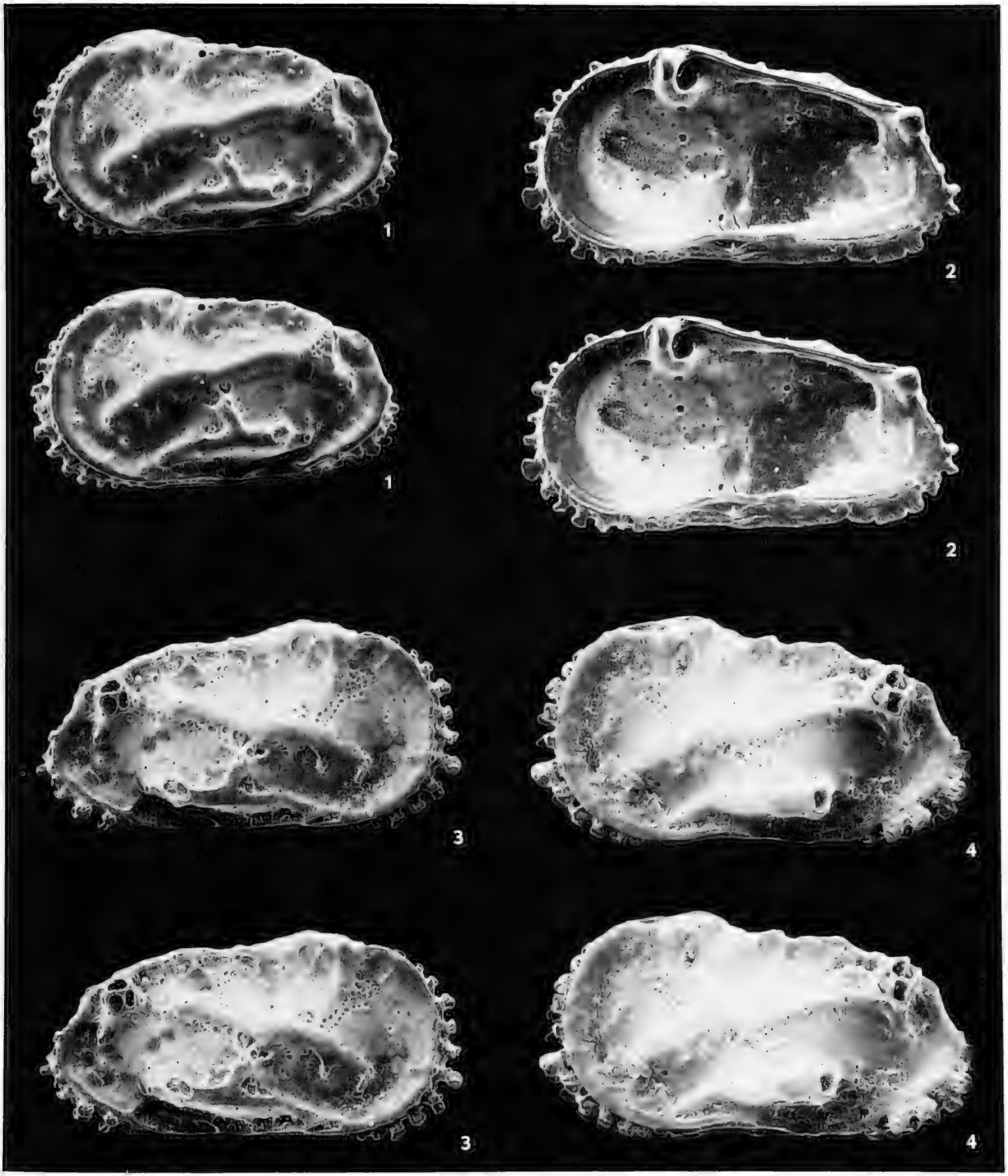
## PLATE 6

*Neocaudites triplistriatus* (Edwards, 1944)

1. Left exterior view female carapace, USNM 172753, type locality of the Duplin Formation, near Magnolia, North Carolina, locality 1 of Edwards (1944), USGS 23639, × 137.

*Neocaudites angulatus*, new species

2. Interior view female right valve, USNM 191388, type locality of the Duplin Formation, near Magnolia, North Carolina, locality 1 of Edwards (1944), USGS 23639, × 110.
3. Exterior view male? right valve, USNM 172741, Croatan Formation, near James City, North Carolina, locality 80 of Waller (1969), USGS 25443, × 102.
4. Left exterior view female carapace, holotype, USNM 172742, Waccamaw Formation, near Old Dock, North Carolina, locality NC-4 of Swain (1968), USGS 25445, × 110.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## PLATE 7

*Neocaudites variabilus*, new species

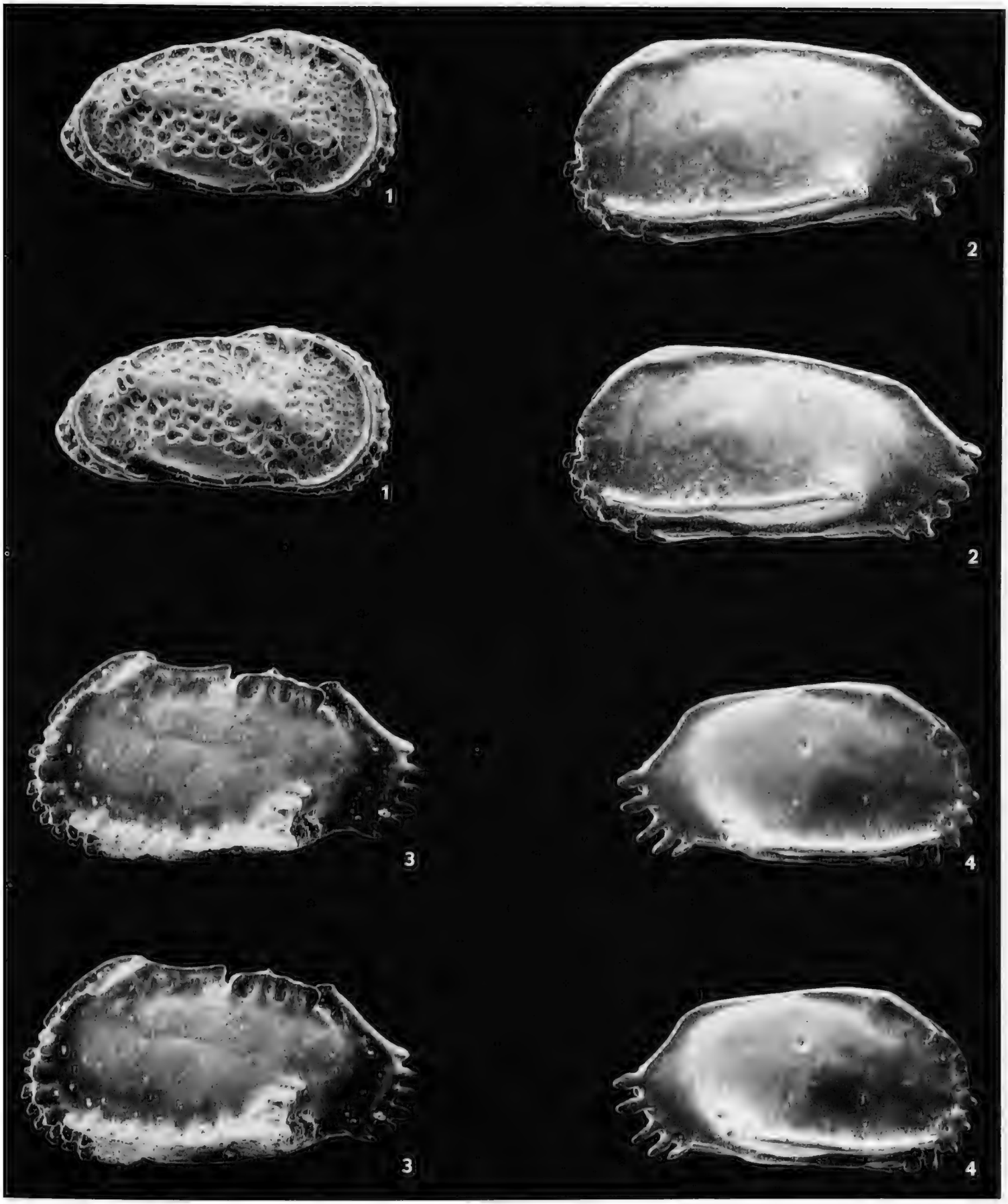
1. Exterior view female right valve, holotype, USNM 190494, type locality of the Duplin Formation, near Magnolia, North Carolina, locality 1 of Edwards (1944), USGS 23639, × 87.

*Pterygocythereis alophia*, new species

2. Exterior view male left valve, USNM 191496, "Yorktown" Formation, Colerain Landing, North Carolina, sample 14 of Hazel (1971a), USGS 24891, × 81.
4. Exterior view female right valve, holotype, USNM 172642, Holocene sample 1861 from Raleigh Bay, south of Cape Hatteras, 34°45.6′ N lat., 75°44.6′ W long., 41 meters, × 78.

*Pterygocythereis inexpectata* (Blake, 1929)

3. Exterior view female left valve, USNM 172748, Yorktown Formation, sample 6 of this study, USGS 24883, × 66.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## PLATE 8

*Actinocythereis captionis*, new species

1. Left exterior view female carapace, holotype, USNM 172461, Holocene sample 2251, southwest of Cape Fear, 33°42.7′ N lat., 78°45.0′ W long., 12 meters, × 85.
2. Left exterior view male carapace, USNM 172463, Holocene sample 2251, southwest of Cape Fear, 33°42.7′ N lat., 78°45.0′ W long., 12 meters, × 90.
4. Interior view male right valve, USNM 191348, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 90.

*Actinocythereis marylandica* (Howe and Hough, 1935)

3. Exterior view female left valve, USNM 190459, Yorktown Formation, near Palmyra, North Carolina, sample 11 of Hazel (1971a), USGS 24889, × 87.

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## PLATE 9

*Actinocythereis dawsoni* (Brady, 1870)

1. Exterior view female left valve, USNM 190458, Yorktown Formation, James City County, Virginia, sample 42 of Hazel (1971a), USGS 24912, × 87.

*Actinocythereis mundorffi* (Swain, 1951)

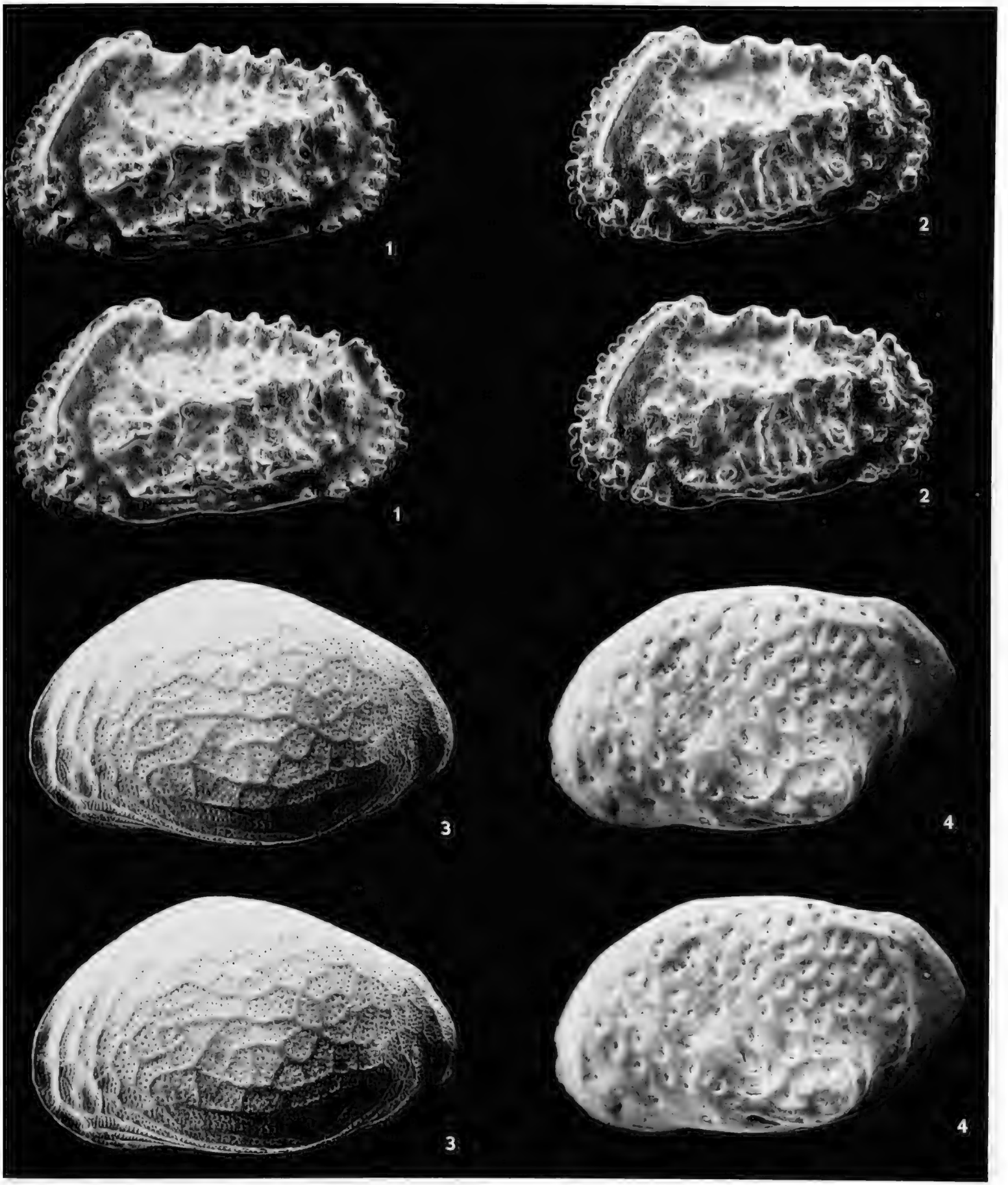
2. Exterior view female left valve, small form, USNM 190457, Yorktown Formation, James City County, Virginia, sample 42 of Hazel (1971a), USGS 24912, × 85.

*Cytheropteron? yorktownensis* (Malkin, 1953)

3. Exterior view female left valve, USNM 190980, Yorktown Formation at Suffolk, Virginia, sample 29 of Hazel (1971a), × 180.

*Cytheropteron talquinensis* (Puri, 1954)

4. Exterior view female left valve, USNM 190981, Yorktown Formation, Williamsburg, Virginia, sample 44 of Hazel (1971a), USGS 24820, × 137.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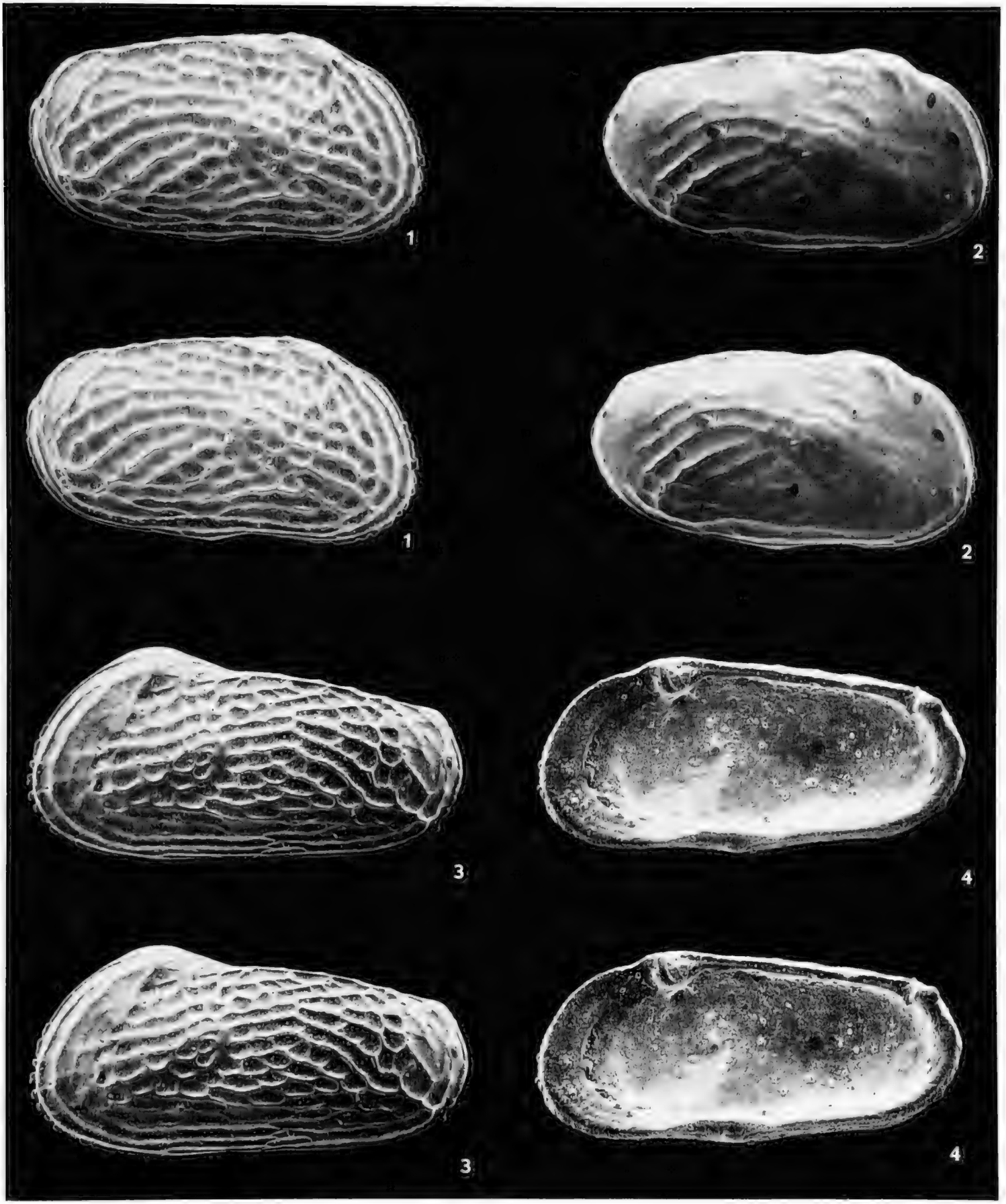
## PLATE 10

*Murrayina macleani* Swain, 1974

1. Exterior view female right valve, ornate form, USNM 172630, Yorktown Formation, sample 4 of this study, USGS 24881, × 95.
2. Exterior view female right valve, smooth form, USNM 172630, Yorktown Formation, Suffolk, Virginia, sample 28 of Hazel (1971a), USGS 24811, × 95.
3. Exterior view male left valve, ornate form, USNM 191395, Yorktown Formation, Suffolk, Virginia, sample 28 of Hazel (1971a), USGS 24811, × 90.
4. Interior view male right valve, USNM 191394, Yorktown Formation, near Skippers, Virginia, sample 27 of Hazel (1971a), USGS 24830, × 82.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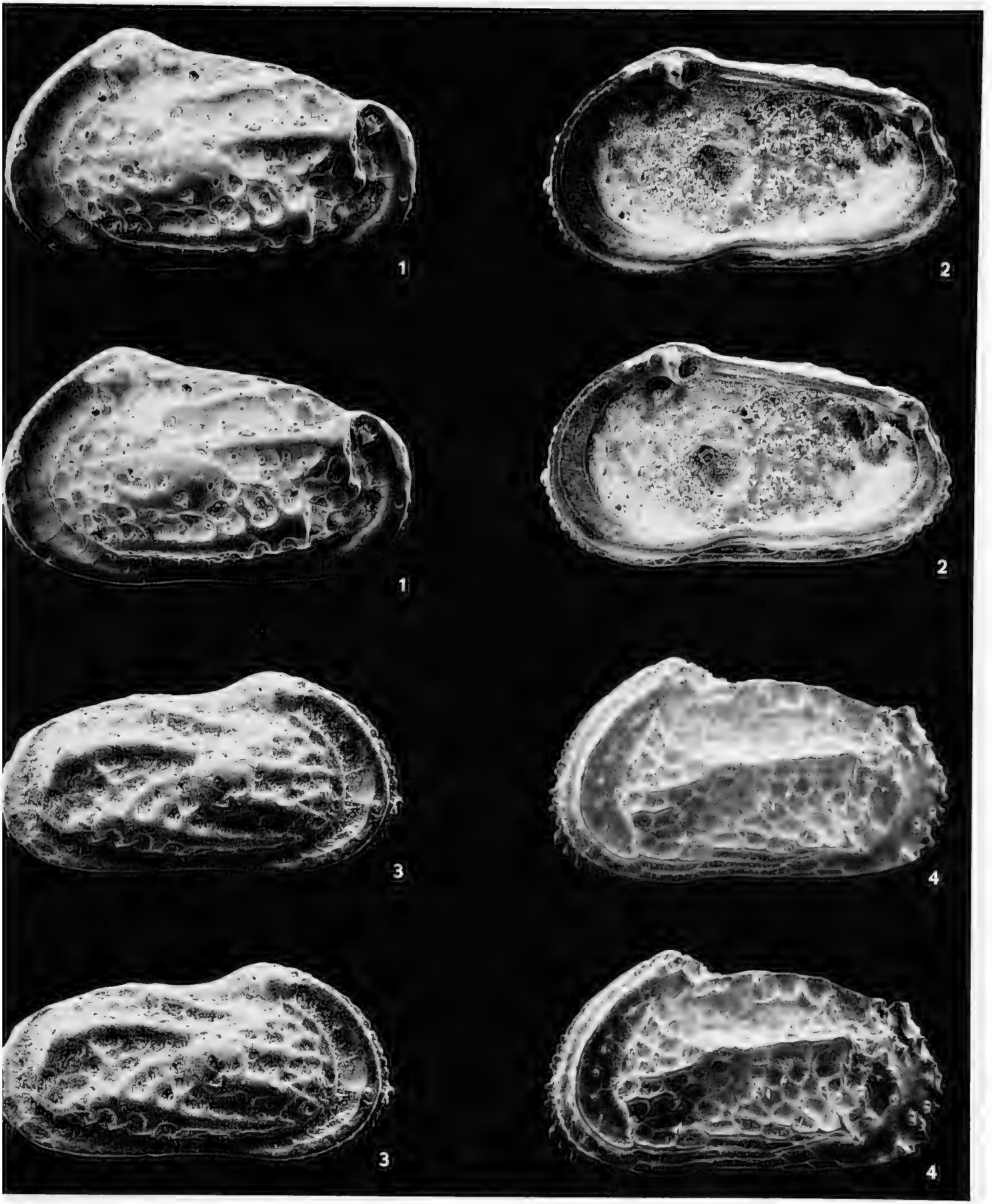
## PLATE 11

*Hermanites ascitus*, new species

1. Exterior view female left valve, holotype, USNM 172745, Duplin Formation, left bank of Lumber River near Lumberton, North Carolina, USGS 25751, × 122.
2. Interior view female right valve, USNM 191016, Duplin Formation, Robeson Farm near Tar Heel, North Carolina, USGS 25755, × 122.
3. Exterior view male right valve, USNM 191333, Yorktown Formation, sample 9 of this study, USGS 25358, × 127.

*Murrayina barclayi* McLean, 1957

4. Exterior view female left valve, USNM 172755, Yorktown Formation at Petersburg, Virginia, sample 38 of Hazel (1971a), USGS 24908, × 88.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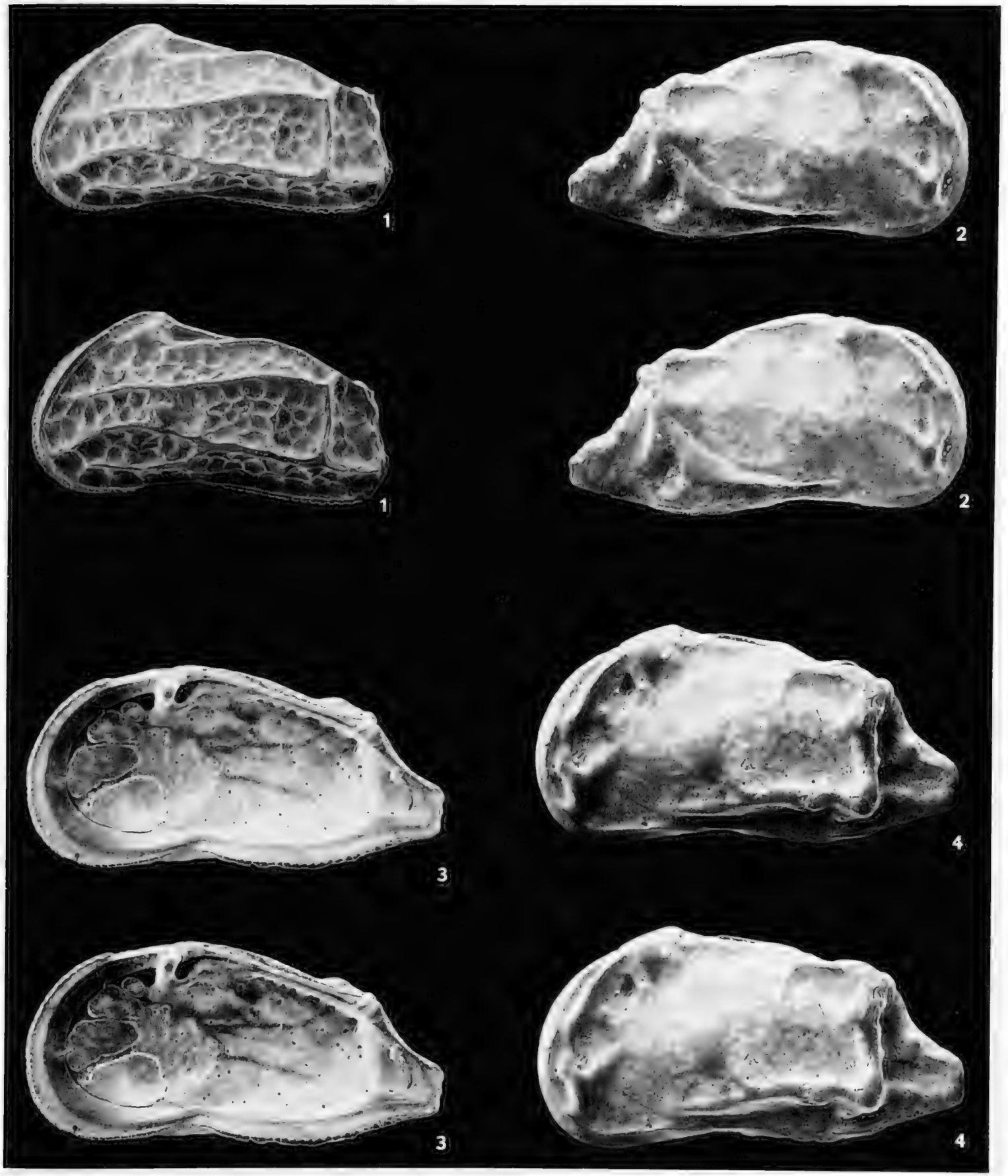
## PLATE 12

*Orionina vaughani* (Ulrich and Bassler, 1904)

1. Exterior view male left valve, USNM 172477, Yorktown Formation at Williamsburg, Virginia, sample 43 of Hazel (1971a), USGS 24821, × 80.

*Caudites paraasymmetricus*, new species

2. Exterior view female right valve, USNM 172757, Croatan Formation, sample 15 of this study, USGS 25378, × 112.
3. Interior view male right valve, USNM 172740, Croatan Formation, sample 15 of this study, USGS 25378, × 112.
4. Left exterior view female carapace, holotype, USNM, 172756, Croatan Formation, sample 15 of this study, USGS 25378, × 113.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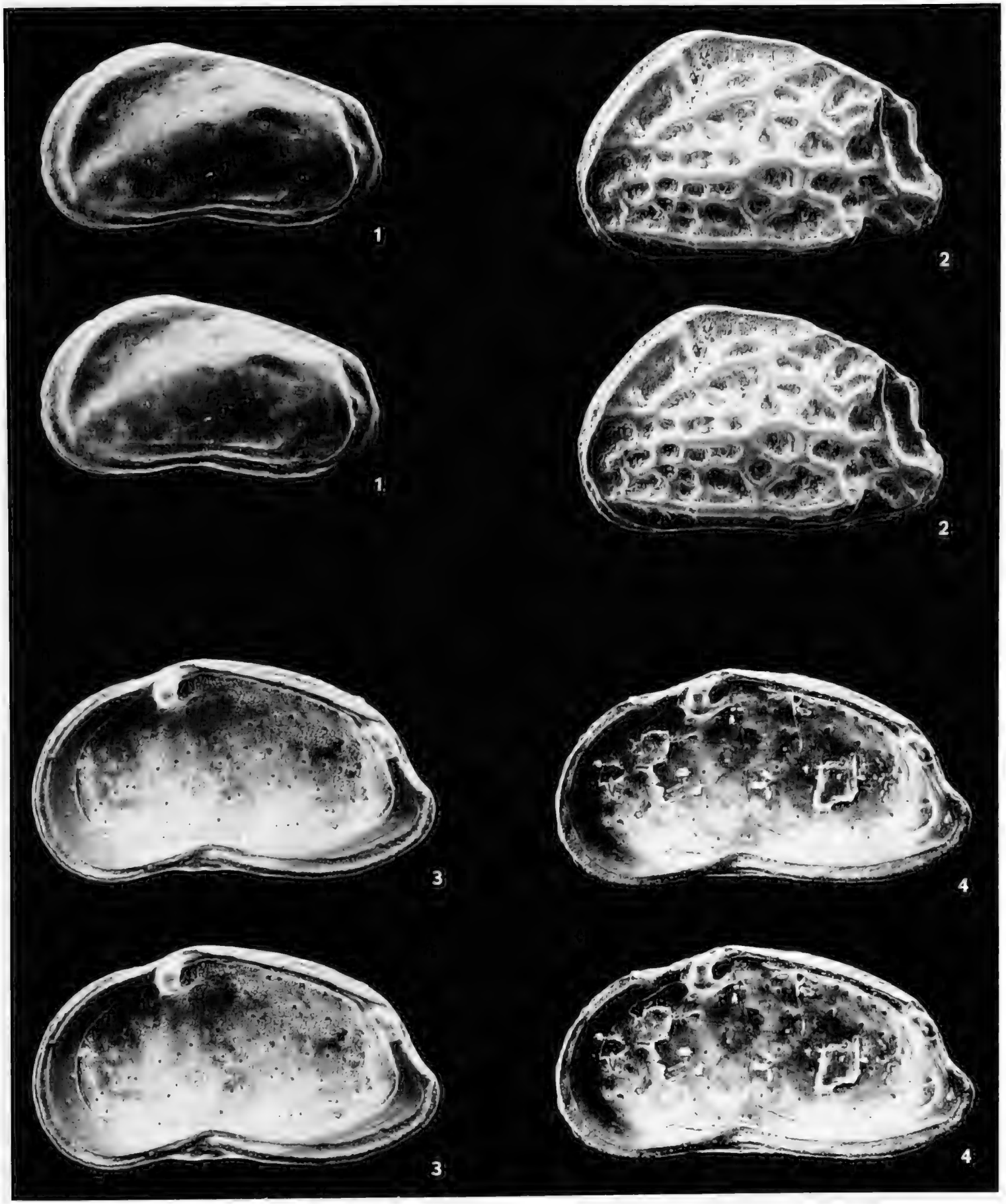
## PLATE 13

*Palaciosa minuta* (Edwards, 1944)

1. Exterior view male left valve, USNM 167401, Croatan Formation, right bank of Neuse River near James City, North Carolina, USGS 25444, × 115.
3. Interior view female right valve, USNM 167403, Croatan Formation, locality 80 of Waller (1969), USGS 25443, × 144.
4. Interior view right valve of disarticulated holotype of Edwards (1944, pl. 87: figs. 1–3), USNM 559425, Duplin Formation near Lumberton, North Carolina. Note that the small pillars in the anterocentral part of the valve in 3 have become centers of calcite deposition in 4, × 144.

*Radimella confragosa* (Edwards, 1944)

2. Left exterior view female carapace, USNM 172675, sample 12 of this study, USGS 24886, × 110.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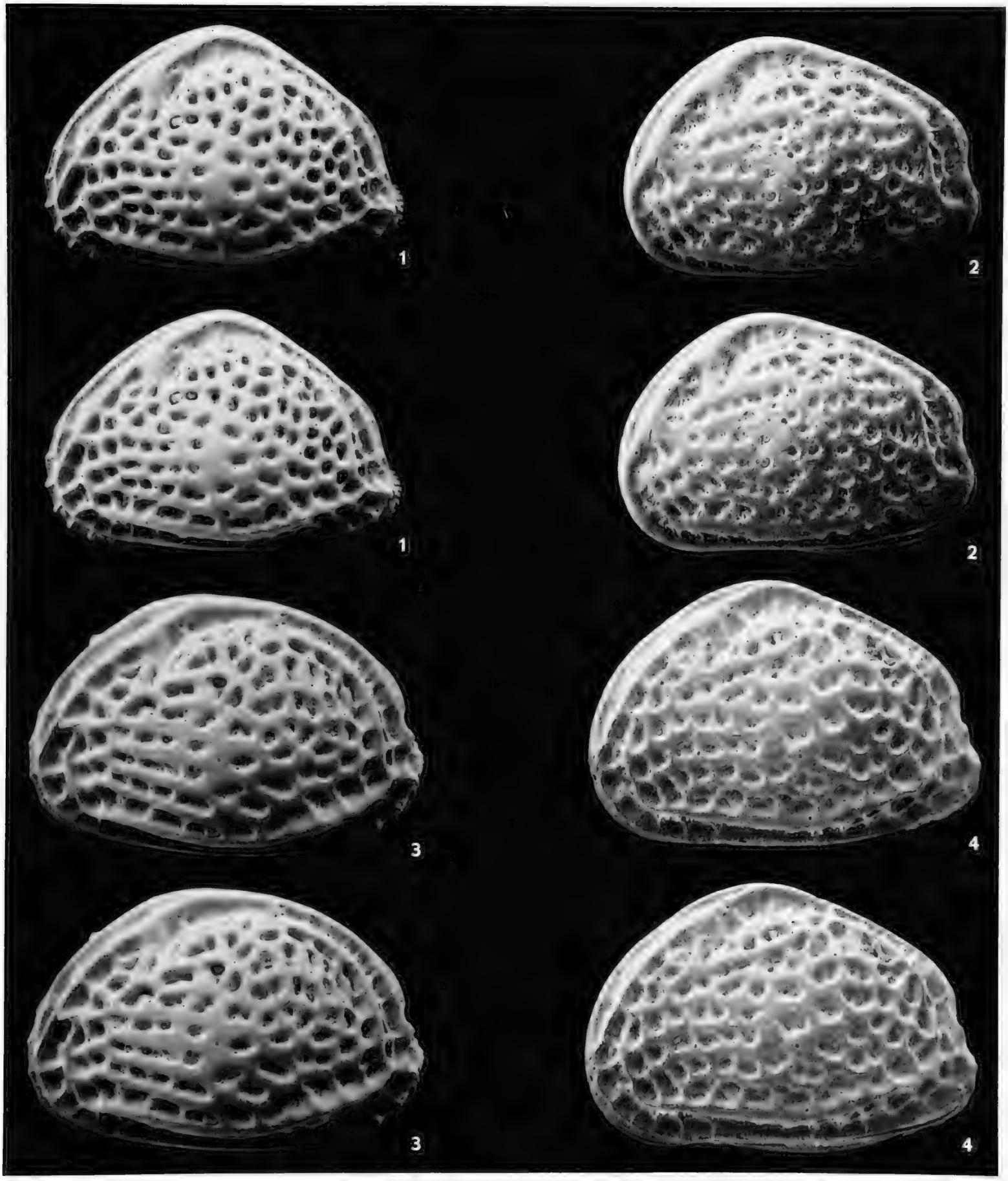
## PLATE 14

*Malzella conradi* (Howe and McGuirt, 1935)

1. Exterior view female left valve, angulate form, USNM 167407, Yorktown Formation at Williamsburg, Virginia, sample 44 of Hazel (1971a), USGS 24820, × 101.
2. Left exterior view female carapace, subquadrate form, USNM 190468, Red Bay Formation of Puri and Vernon (1964), (*Arca* zone), upper Miocene, 1 mile (1.61 km) southeast of Red Bay, Fla., USGS 24709, × 85.
4. Left exterior view female carapace, intermediate form, USNM 190692, Jackson Bluff Formation (*Ecphora* zone), Pliocene, Leon County, Florida, USGS 25158, × 93.

*Malzella evexa*, new species

3. Exterior view female left valve, holotype, USNM 172653, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 95.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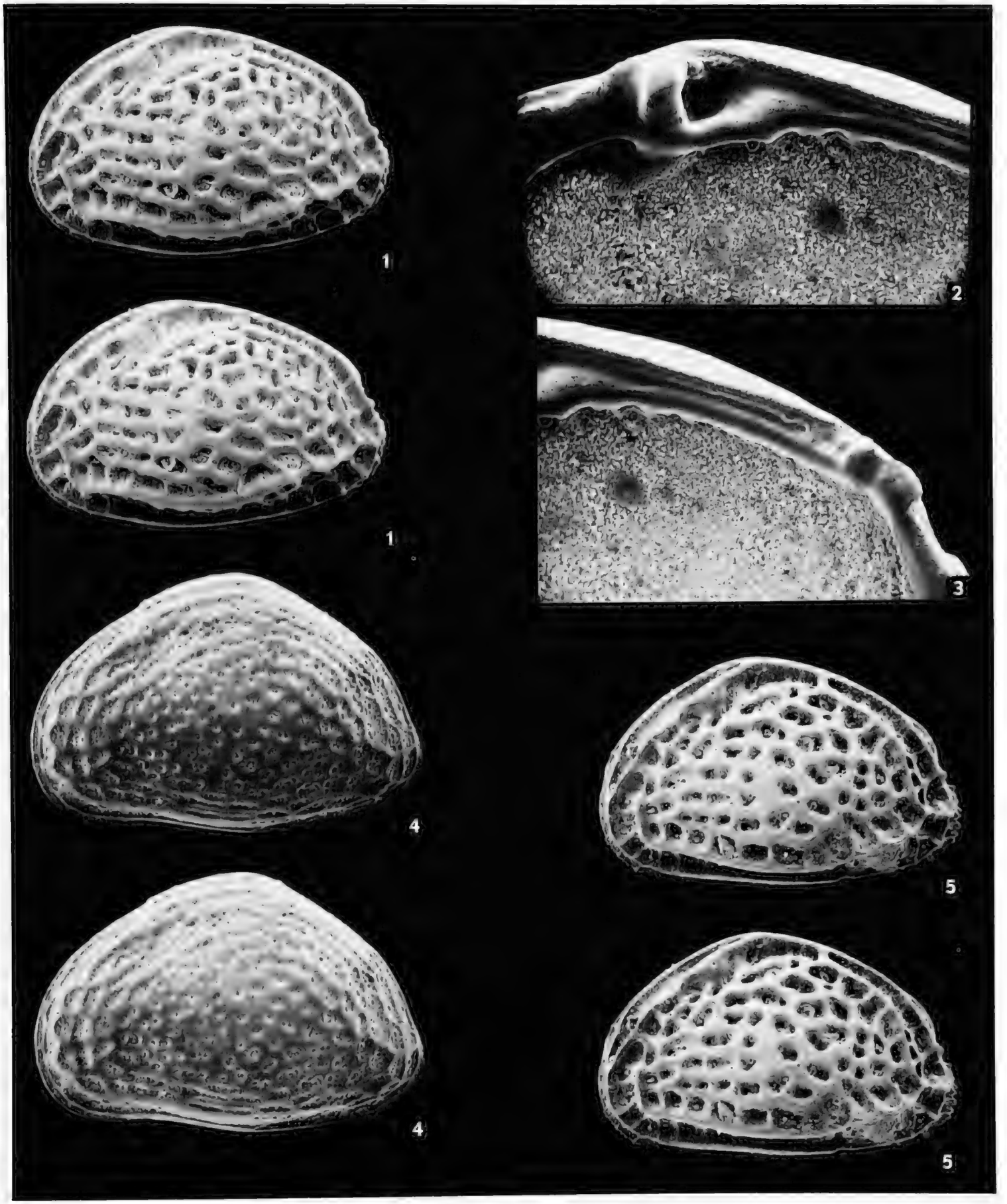
## PLATE 15

*Malzella evexa*, new species

1. Exterior view male left valve, USNM 313689, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 107.
2. Interior view female right valve showing anterior hinge elements, USNM 191340, Duplin Formation, Cedar Bluff Landing on the Savannah River, Georgia, USGS 23863, × 236.
3. Interior view female right valve, same specimen as figure 2 showing posterior hinge elements, × 236.
5. Exterior view female left valve, Edwards' (1944, pl. 86: fig. 18) specimen, USNM 559759, Duplin Formation, near Magnolia, North Carolina, locality 1 of Edwards (1944), × 122.

*Aurila laevicula* (Edwards, 1944)

4. Exterior view female left valve, USNM 172491, Yorktown Formation at Petersburg, Virginia, sample 39 of Hazel (1971a), USGS 24908, × 103.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## PLATE 16

*Muellerina bassiounii*, new species

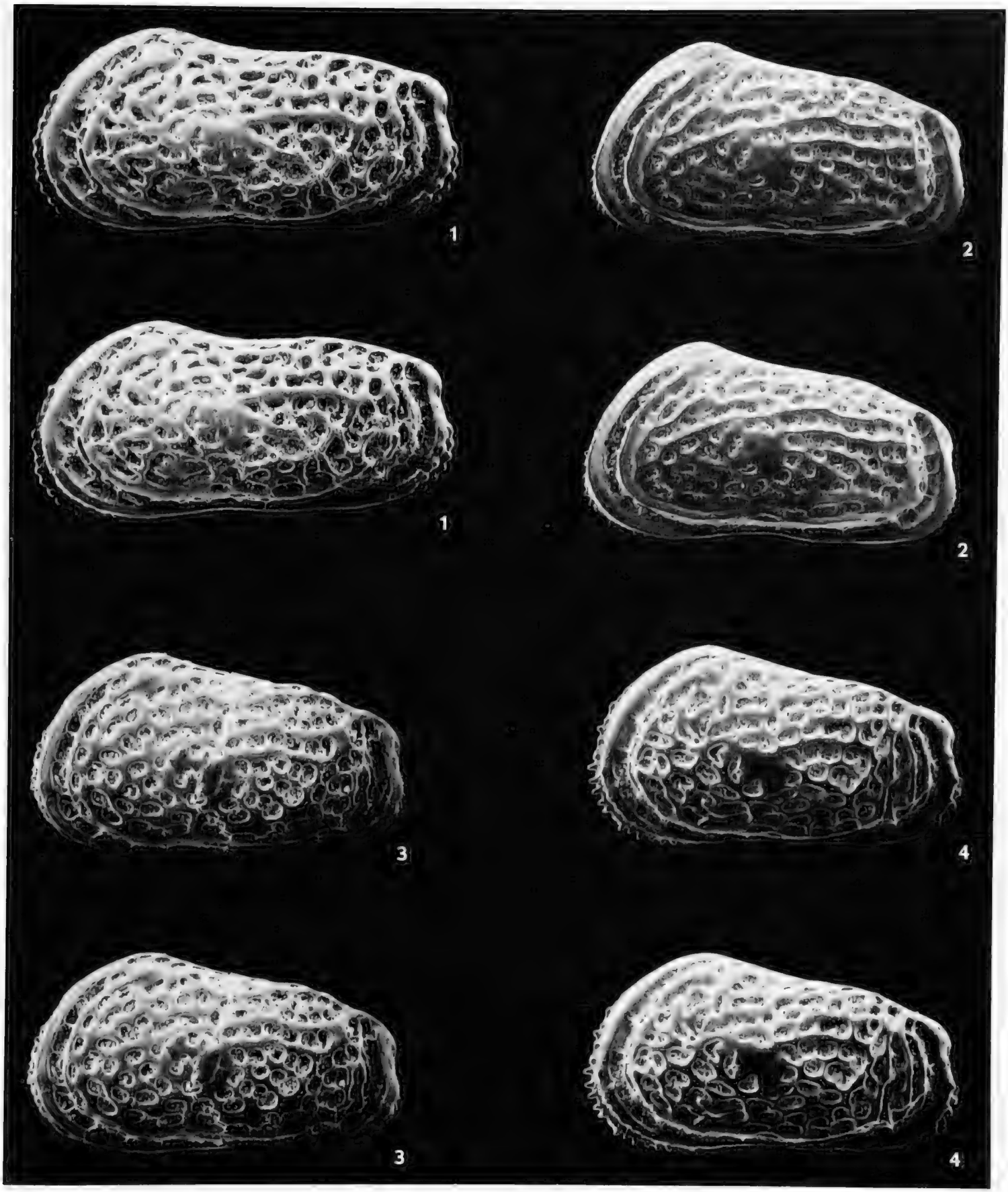
1. Exterior view male left valve, USNM 172618, "Yorktown" Formation near Mt. Gould, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 115.
4. Exterior view female left valve, holotype, USNM 167410, Croatan Formation at its type locality (MacNeil, 1938; DuBar and Solliday, 1963), near James City, North Carolina, × 103.

*Muellerina canadensis petersburgensis*, new subspecies

2. Exterior view female left valve, holotype, USNM 167408, Yorktown Formation at Petersburg, Virginia, sample 38 of Hazel (1971a), USGS 24908, × 103.

*Muellerina ohmerti*, new species

3. Exterior view female left valve, holotype, USNM 112741, Holocene, Atlantic shelf south of Long Island, 40°20′ N lat., 73°15′ W long., 36 meters, sample 1287 of Hazel (1967, 1970), and Valentine (1971), × 95.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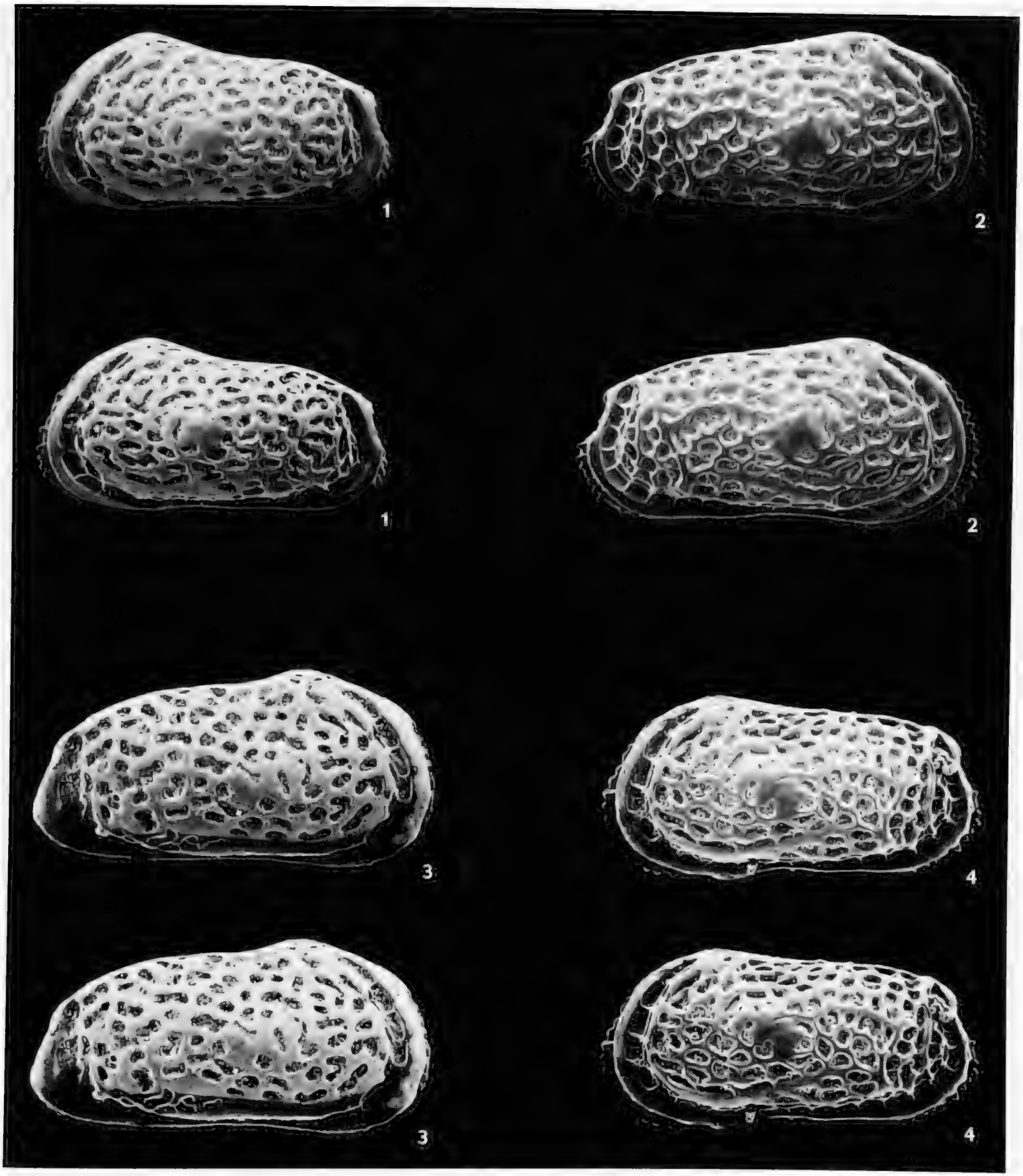
## PLATE 17

*Muellerina blowi*, new species

1. Exterior view female left valve, holotype, USNM 167411, Yorktown Formation at Suffolk, Virginia, sample 29 of Hazel (1971a), USGS 24814, × 92.
3. Exterior view female right valve, USNM 172621, Yorktown Formation at Suffolk, Virginia, sample 29 of Hazel (1971a), USGS 24814, × 98.

*Muellerina wardi*, new species

2. Exterior view female right valve, USNM 172489, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 90.
4. Exterior view female left valve, holotype, USNM 167409, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 88.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## PLATE 18

*Muellerina canadensis petersburgensis*, new subspecies

1. Interior view male right valve, USNM 172625, Yorktown Formation at Petersburg, Virginia, sample 38 of Hazel (1971a), USGS 24908, × 89.
3. Interior view female right valve, USNM 172626, Yorktown Formation at Halifax, North Carolina, sample 24 of Hazel (1971a), USGS 24904, × 91.

*Muellerina blowi*, new species

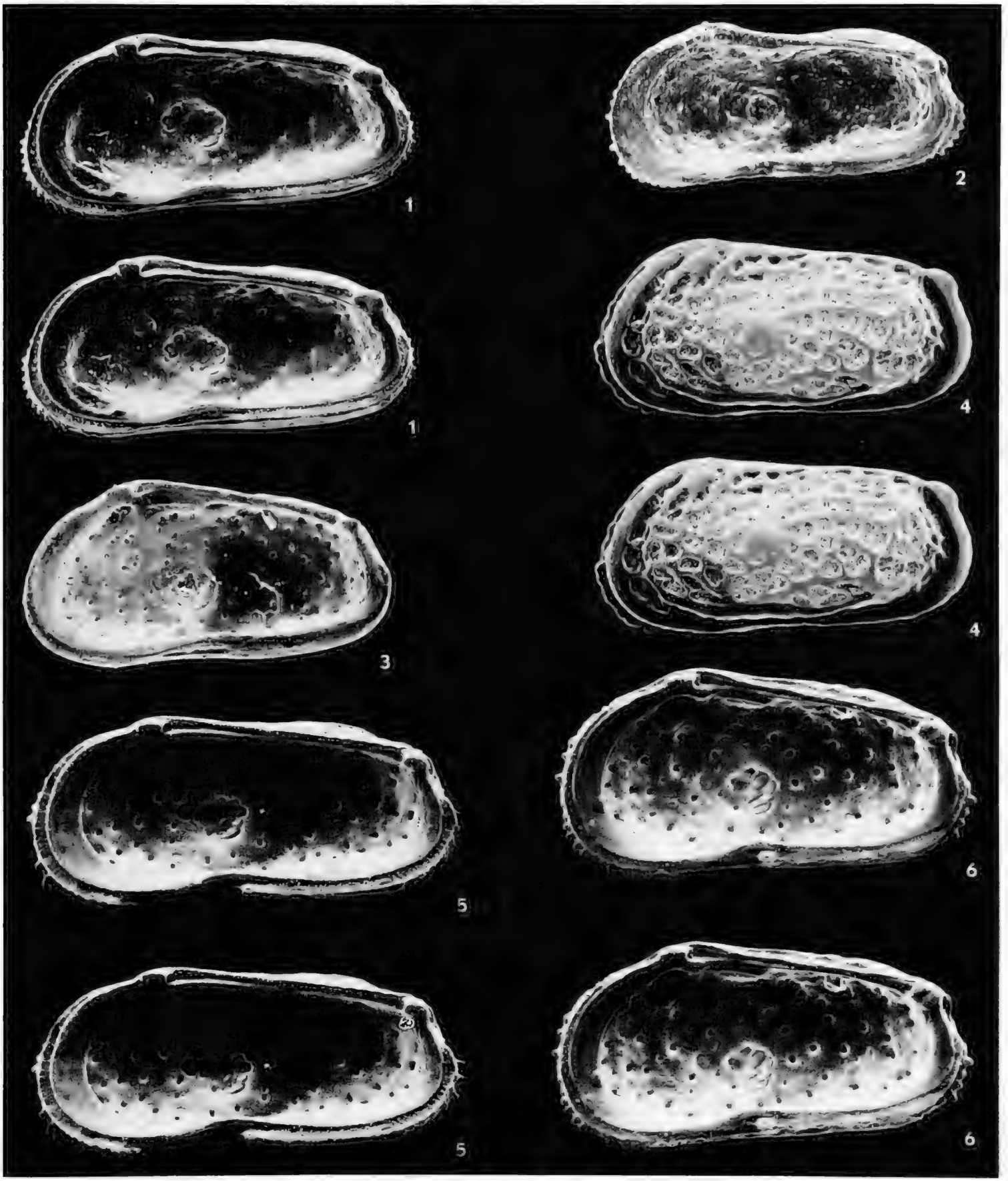
2. Interior view male right valve, USNM 172720, Yorktown Formation at Suffolk, Virginia, sample 29 of Hazel (1971a), USGS 24814, × 102.

*Muellerina wardi*, new species

4. Exterior view male left valve, USNM 172632, Yorktown Formation on the Piankatank River, Middlesex County, Virginia, sample 46 of Hazel (1971a), USGS 24801, × 104.
5. Interior view male right valve, USNM 172634, Yorktown Formation in Petersburg, Virginia, sample 39 of Hazel (1971a), USGS 24909, × 116.

*Muellerina bassiounii*, new species

6. Interior view female right valve, USNM 191402, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 111.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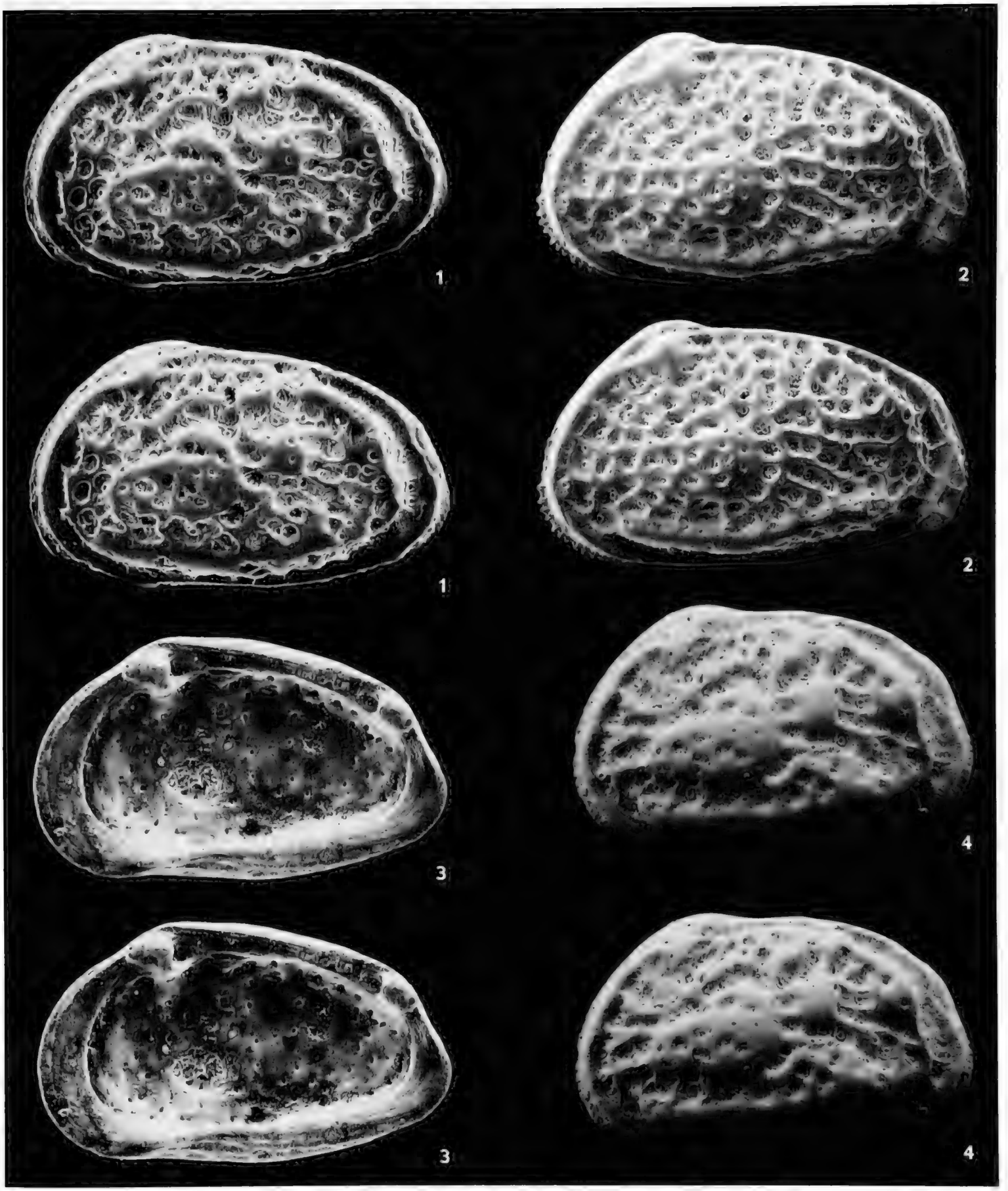
## PLATE 19

*Thaerocythere carolinensis*, new species

1. Exterior view male left valve, USNM 172658, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 16 of Hazel (1971a), USGS 24893, × 108.
3. Interior view female right valve, USNM 191415, "Yorktown" Formation at Colerain Landing, North Carolina, sample 14 of Hazel (1971a), USGS 24891, × 97.
4. Left exterior view female carapace, holotype, USNM 172657, "Yorktown" Formation at Colerain Landing, North Carolina, sample 14 of Hazel (1971a), USGS 24891, × 90.

*Thaerocythere schmidtae* (Malkin, 1953)

2. Exterior view male left valve, USNM 172657, "Yorktown" Formation at Colerain Landing, North Carolina, sample 14 of Hazel (1971a), USGS 24891, × 90.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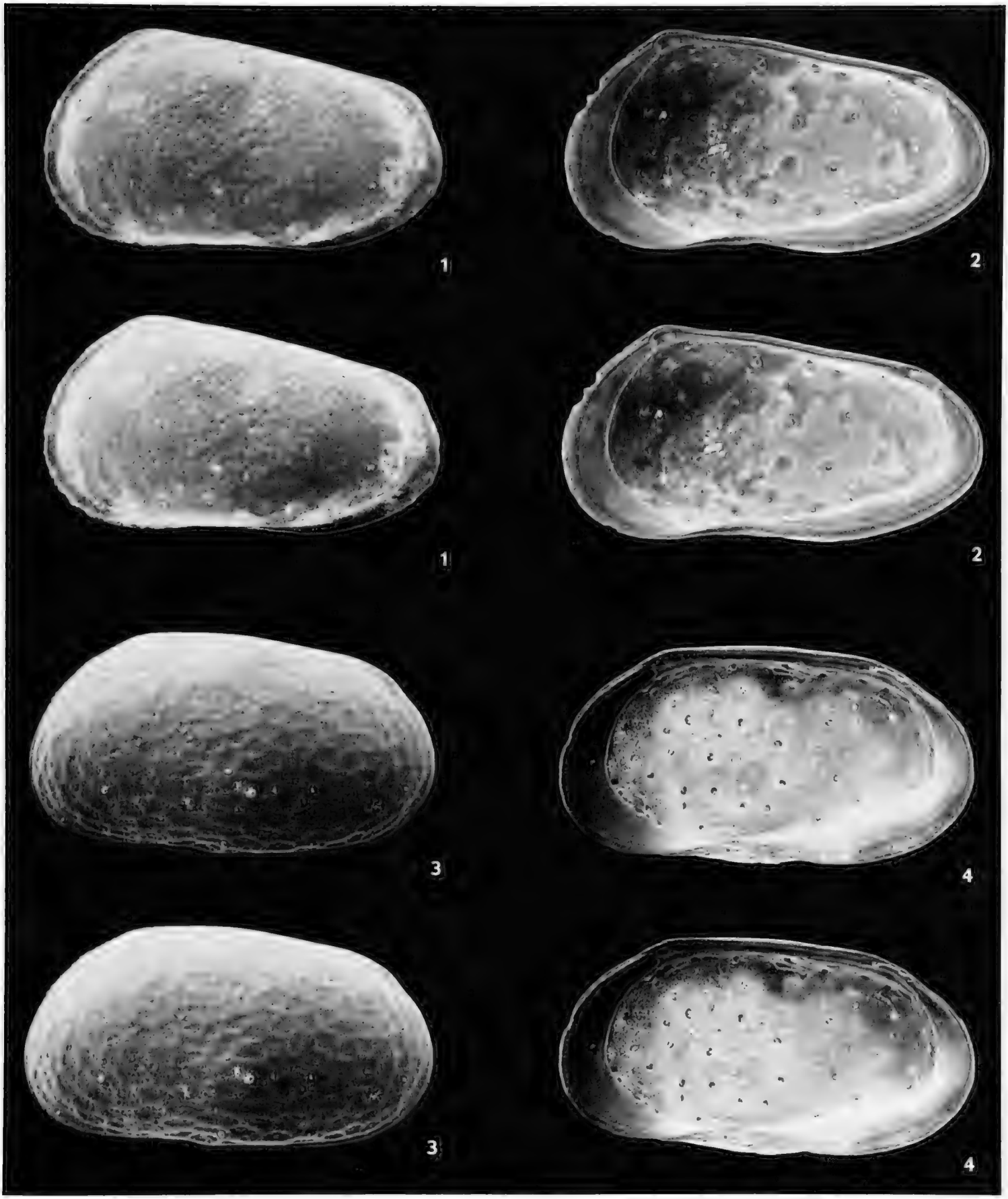
## PLATE 20

*Hirschmannia? hespera*, new species

1. Exterior view female left valve, holotype, USNM 172575, sample 14 of this study, USGS 24887, × 147.
2. Interior view female right valve, USNM 172576, sample 14 of this study, USGS 24887, × 147.

*Hirschmannia? quadrata*, new species

3. Exterior view female left valve, holotype, USNM 172571, "Yorktown" Formation near Yadkin, Virginia, sample 31 of Hazel (1971a), USGS 24905, × 149.
4. Interior view male right valve, USNM 172573, "Yorktown" Formation near Yadkin, Virginia, sample 31 of Hazel (1971a), USGS 24905, × 166.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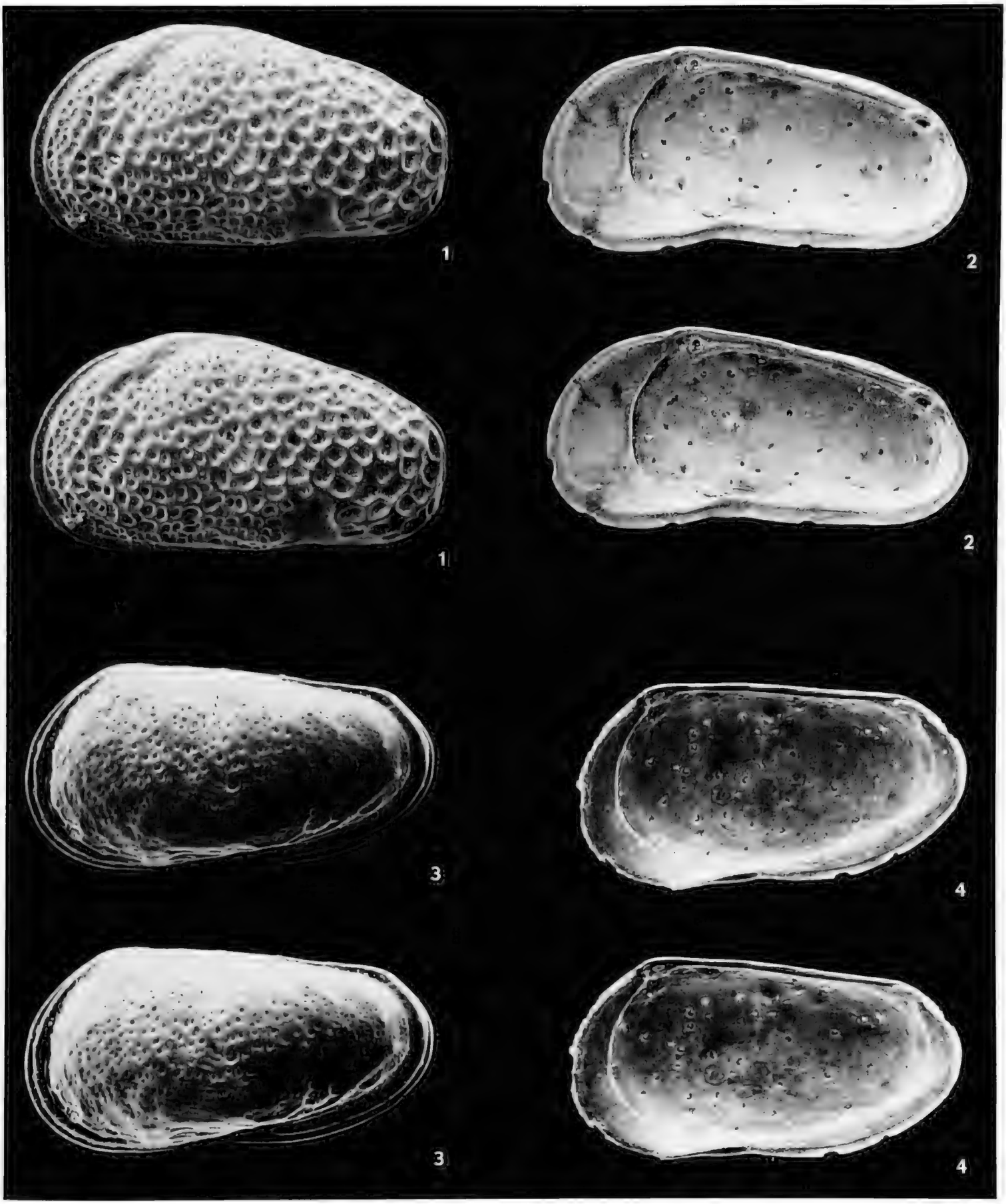
## PLATE 21

*Cytheromorpha incisa*, new species

1. Exterior view female left valve, holotype, USNM 172560, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 18 of Hazel (1971a), USGS 24895, × 136.
2. Interior view male right valve, USNM 172559, "Yorktown" Formation, Colerain Landing, North Carolina, sample 15 of Hazel (1971a), USGS 24892, × 136.

*Hirschmannia? hespera*, new species

3. Exterior view male left valve, USNM 172574, Croatan Formation, sample 14 of this study, USGS 24887, × 168.
4. Interior view female right valve, USNM 172577, Croatan Formation, sample 14 of this study, USGS 24887, × 154.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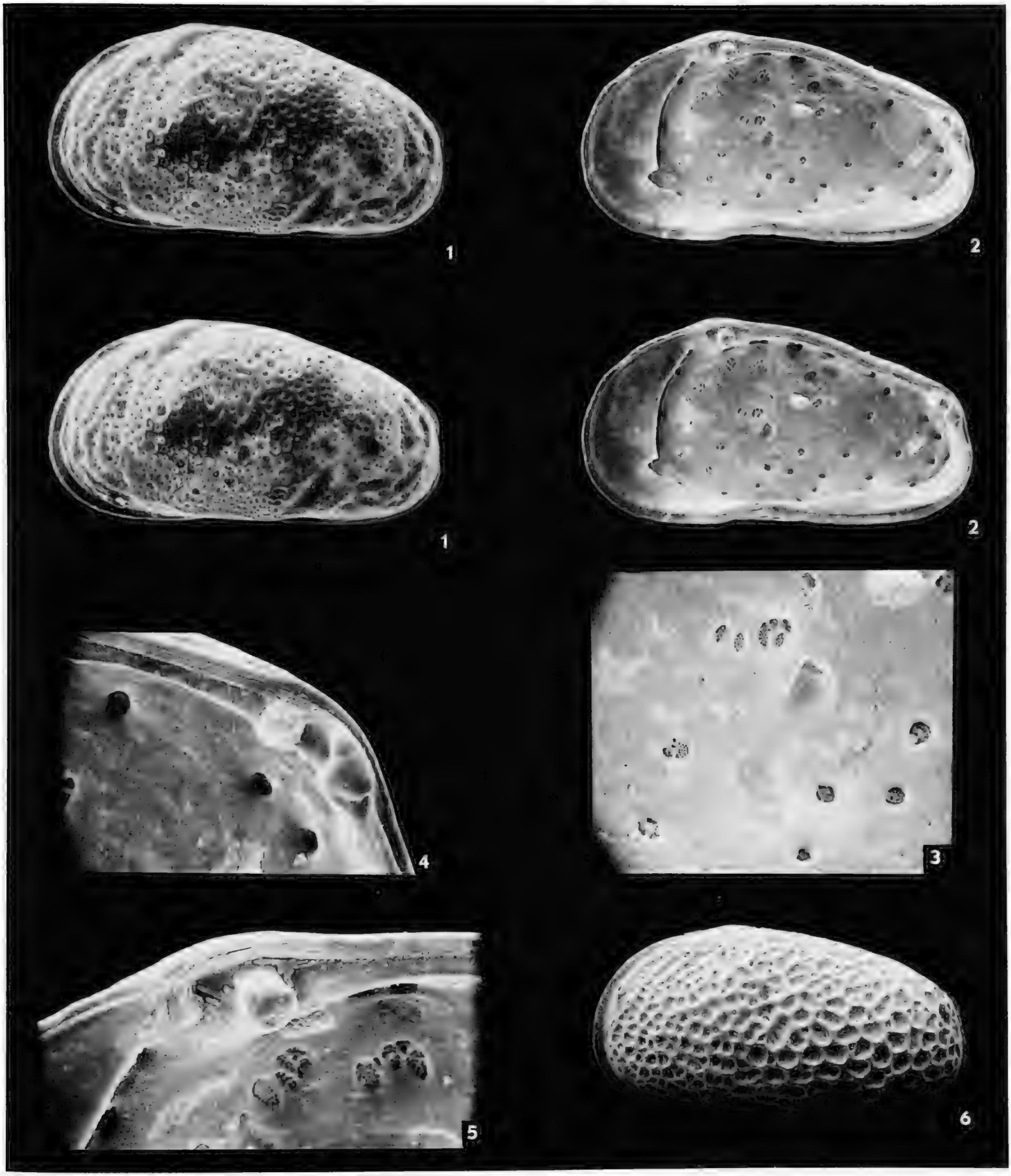
## PLATE 22

*Cytheromorpha macroincisa*, new species

1. Exterior view female left valve, holotype, USNM 172562, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 18 of Hazel (1971a), USGS 24895, × 116.
2. Interior view female right valve, USNM 172561, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 18 of Hazel (1971a), USGS 24895, × 118.
3. Interior view female right valve, showing central muscle field, same specimen as figure 2, × 356.
4. Interior view female right valve, showing posterior hinge elements, same specimen as figure 2, × 390.
5. Interior view female right valve, showing anterior hinge elements, same specimen as figure 2, × 390.

*Cytheromorpha warneri* Howe and Spurgeon, 1935

6. Exterior view female left valve, USNM 172555, Jackson Bluff Formation (*Ecphora* zone), Leon County, Florida, USGS 25158, × 105.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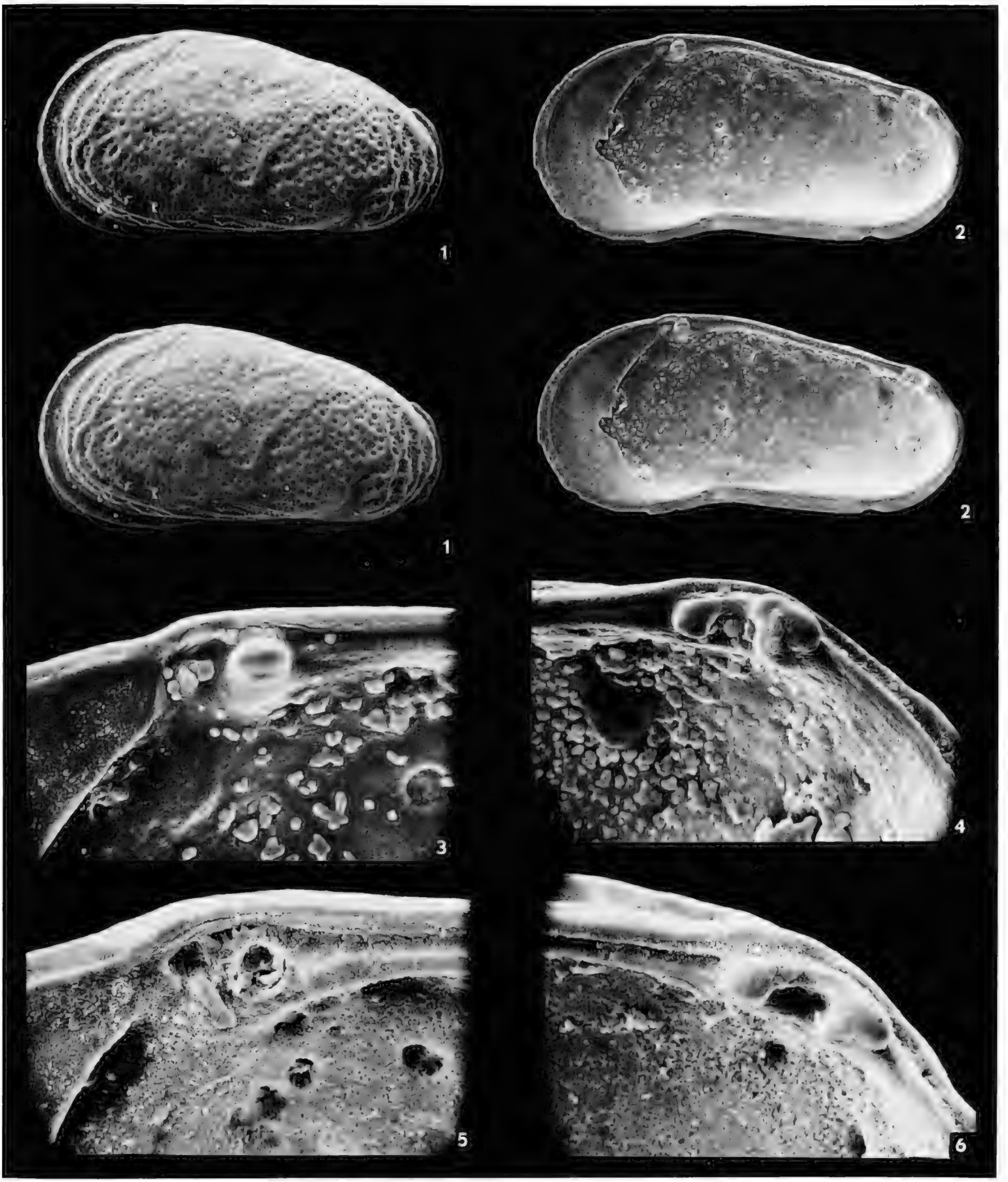
## PLATE 23

*Cytheromorpha suffolkensis*, new species

1. Exterior view female left valve, holotype, USNM 172551, Yorktown Formation, Suffolk, Virginia, sample 29 of Hazel (1971a), USGS 24814, × 142.
2. Interior view male right valve, USNM 172552, Yorktown Formation, Suffolk, Virginia, sample 29 of Hazel (1971a), USGS 24814, × 142.
3. Interior view male right valve, showing anterior hinge elements, same specimen as figure 2, × 600.
4. Interior view male right valve, showing posterior hinge elements, same specimen as figure 2, × 600.

*Cytheromorpha incisa*, new species

5. Interior view male right valve, showing anterior hinge elements, USNM 172559, "Yorktown" Formation, Colerain Landing, North Carolina, sample 15 of Hazel (1971a), USGS 24892, × 544.
6. Interior view male right valve, showing posterior hinge elements, same specimen as figure 5, × 544.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## PLATE 24

*Pseudocytheretta burnsi* (Ulrich and Bassler, 1904)

1. Exterior view male left valve, smooth form, USNM 172638, Yorktown Formation, Hampton City, Virginia, sample 36 of Hazel (1971a), USGS 24907, × 70.
3. Right exterior view female carapace, pitted form, USNM 172637, Yorktown Formation, Hampton City, Virginia, sample 36 of Hazel (1971a), USGS 24907, × 75.

*Loxoconcha edentonensis* Swain, 1951

2. Exterior view female left valve, USNM 172603, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 19 of Hazel (1971a), USGS 24896, × 120.
4. Exterior view male left valve, USNM 172604, Croatan Formation, sample 12 of this study, USGS 24886, × 120.

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## PLATE 25

*Proteoconcha jamesensis*, new species

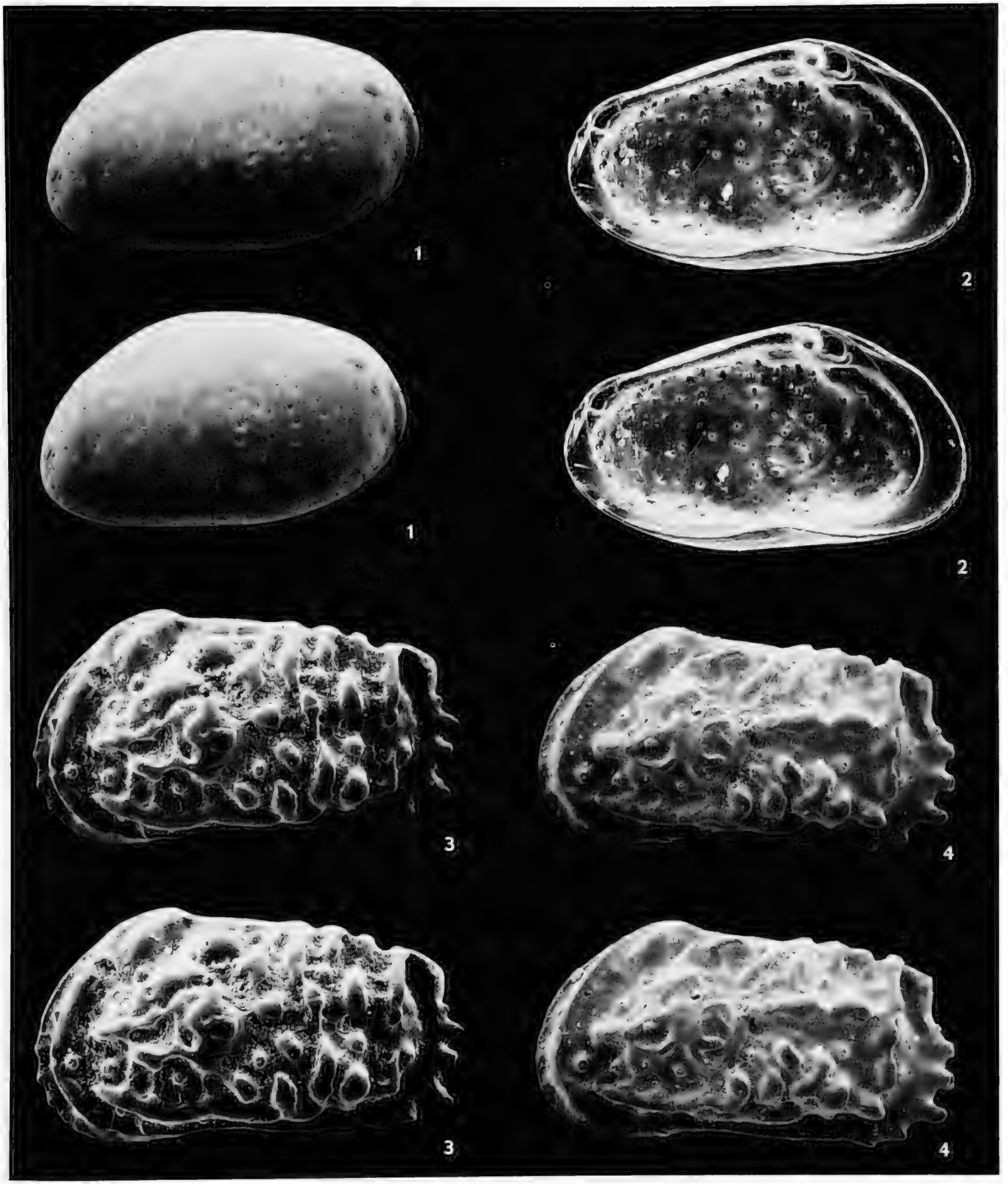
1. Exterior view female left valve, holotype, USNM 167377, Yorktown Formation, Nansemond County, Virginia, sample 32 of Hazel (1971a), USGS 24622, × 90.
2. Interior view female left valve, USNM 191438, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 17 of Hazel (1971a), USGS 24894, × 108.

*Puriana rugipunctata* (Ulrich and Bassler, 1904)

3. Exterior view female left valve, USNM 172669, Yorktown Formation at Petersburg, Virginia, sample 38 of Hazel (1971a), USGS 24908, × 110.

*Puriana mesacostalis* (Edwards, 1944)

4. Exterior view female left valve, USNM 172668, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 112.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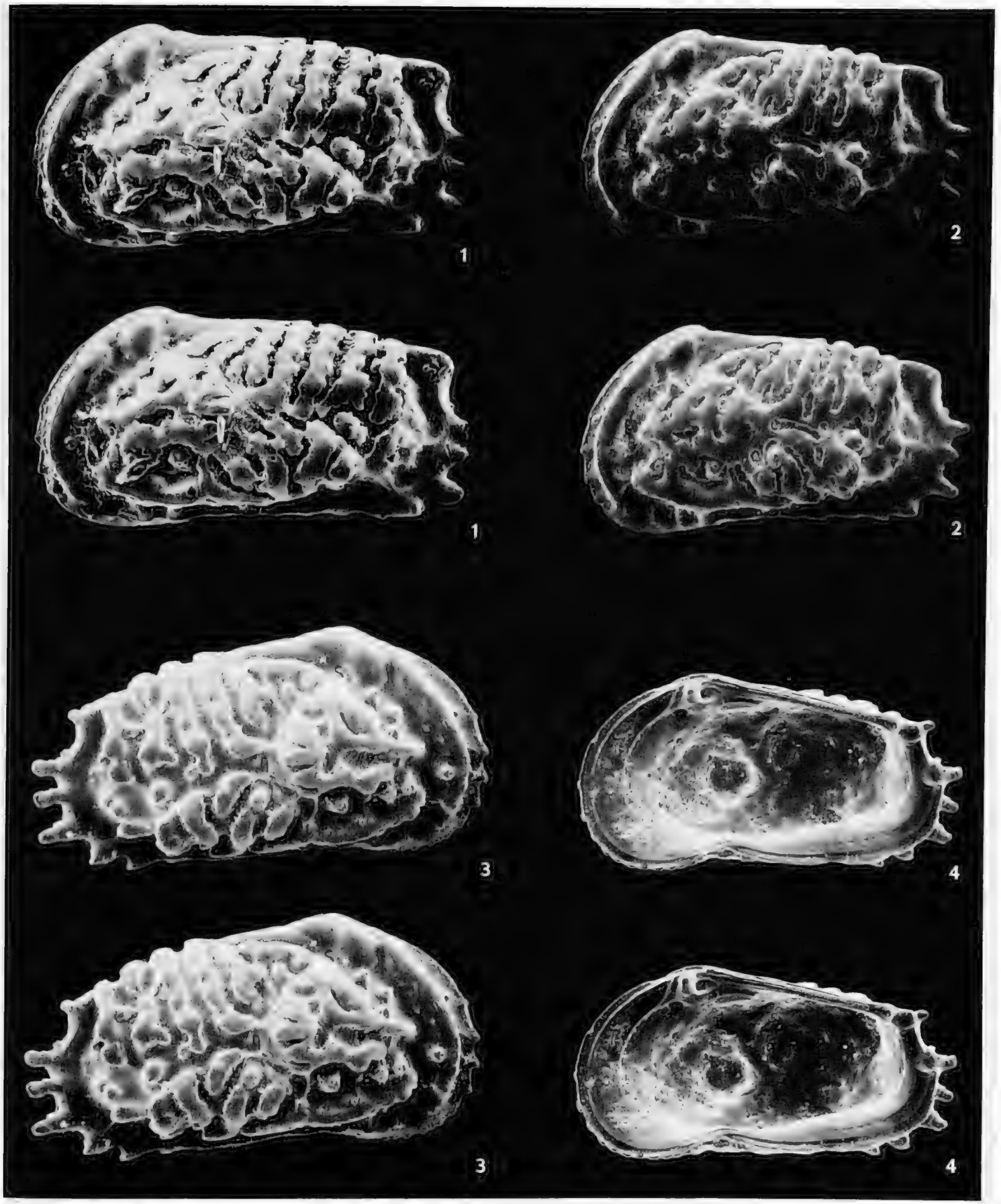
## PLATE 26

*Puriana convoluta* Teeter, 1975

1. Exterior view male left valve, USNM 191499, Waccamaw Formation, Old Dock, North Carolina, USGS 25445, × 130.
2. Exterior view female left valve, USNM 172651, Holocene sample 1861, Raleigh Bay, south of Cape Hatteras, 34°45.6′ N lat., 75°44.6′ W long., 41 meters, × 115.
4. Interior view female right valve, USNM 172652, Holocene sample 1861, Raleigh Bay, south of Cape Hatteras, 34°45.6′ N lat., 75°44.6′ W long., 41 meters, × 113.

*Puriana rugipunctata* (Ulrich and Bassler, 1904)

3. Exterior view female right valve, USNM 172478, Yorktown Formation, Williamsburg, Virginia, sample 44 of Hazel (1971a), USGS 24820, × 135.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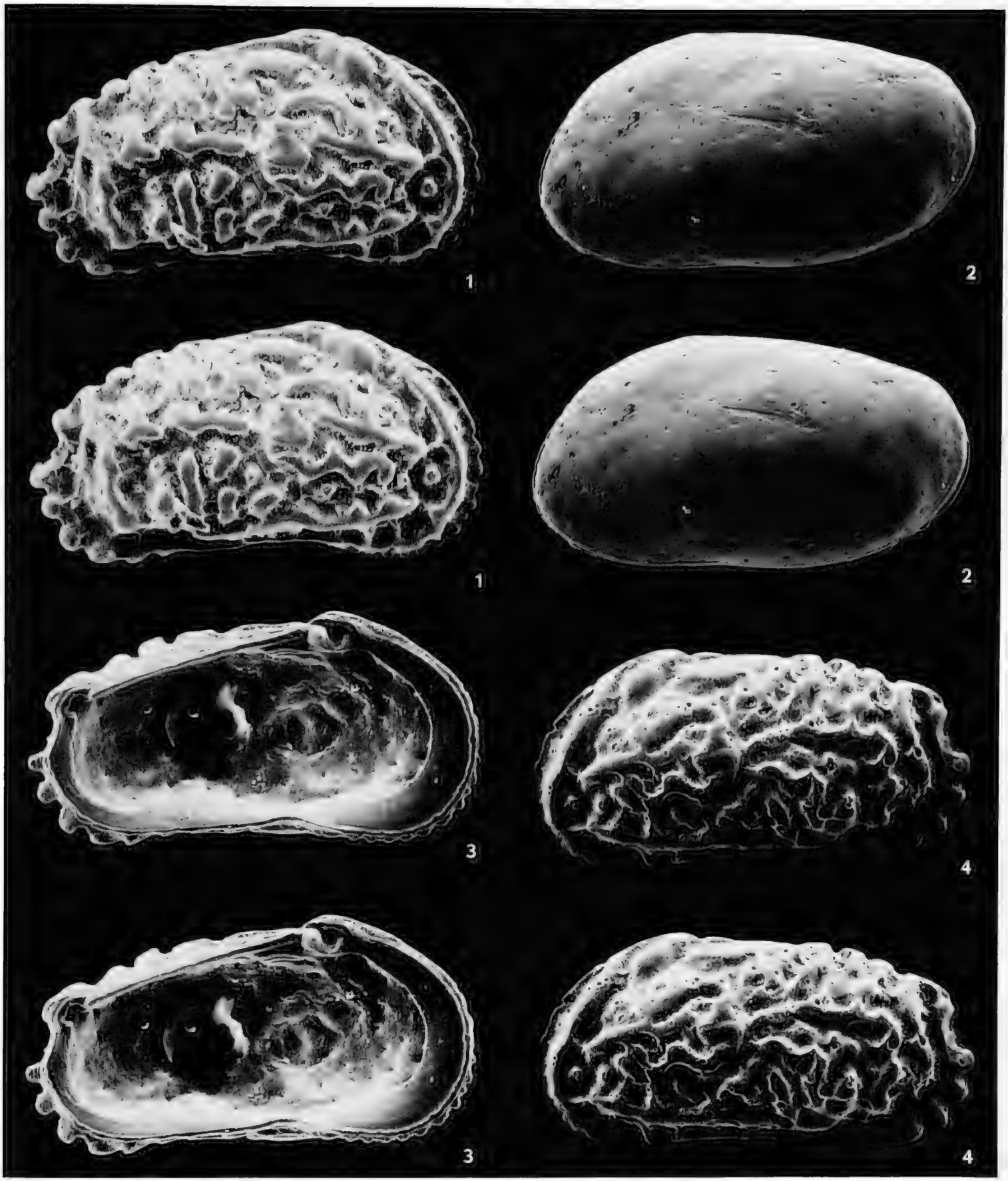
## PLATE 27

*Puriana carolinensis*, new species

1. Exterior view female right valve, holotype, USNM 172649, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 109.
3. Interior view female left valve, USNM 172647, type locality of the Duplin Formation, near Magnolia, North Carolina, USGS 23639, × 150.
4. Exterior view male left valve, USNM 172648, type locality of the Duplin Formation, near Magnolia, North Carolina, USGS 23639, × 150.

*Proteoconcha jamesensis*, new species

2. Exterior view male left valve, USNM 167379, Yorktown Formation, Hampton City, Virginia, sample 36 of Hazel (1971a), USGS 24907, × 117.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## PLATE 28

*Paracytheridea cronini*, new species

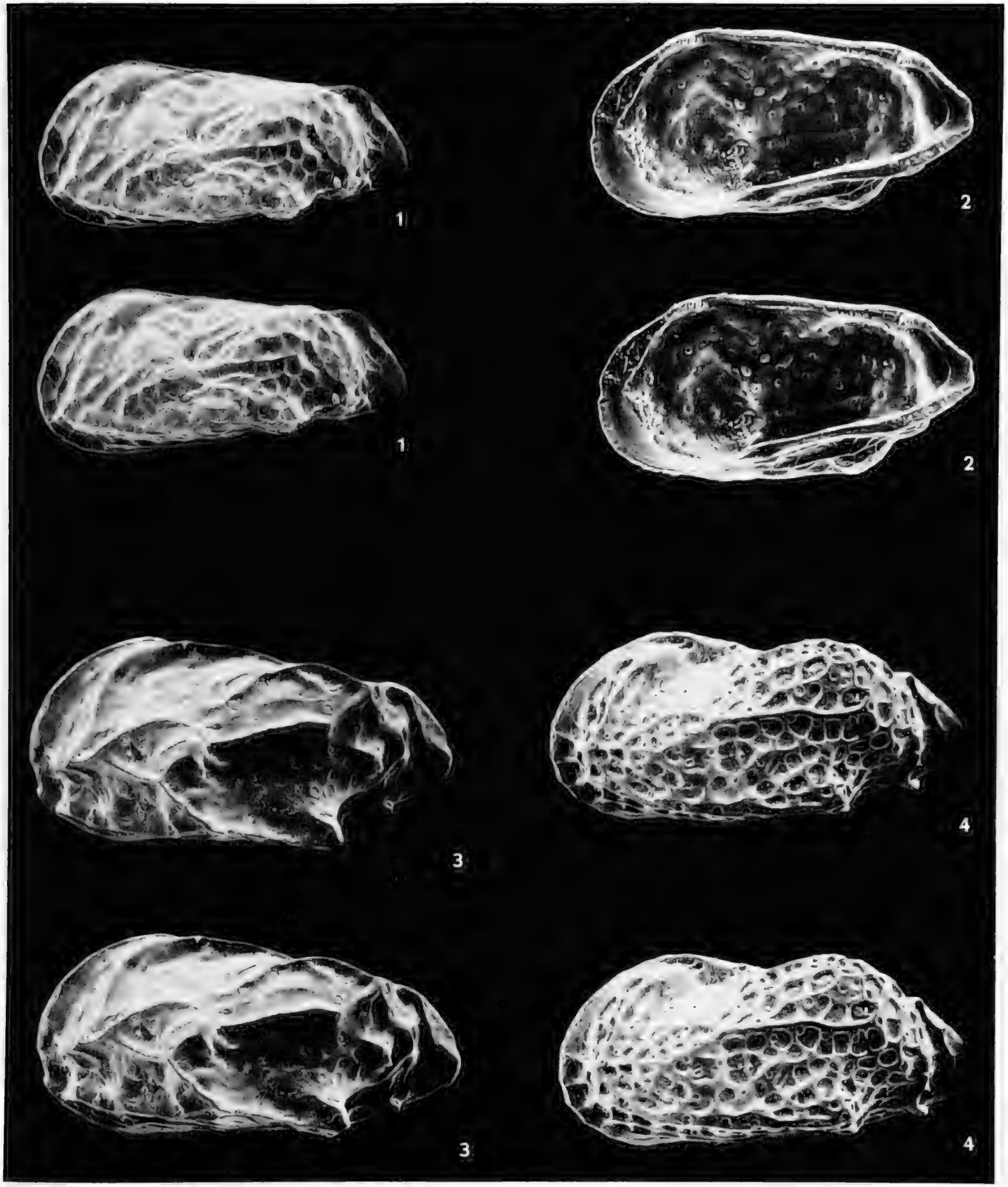
1. Exterior view male left valve, USNM 191428, type locality of the Duplin Formation, near Magnolia, North Carolina, USGS 23639, × 115.
2. Interior view female right valve, USNM 191412, type locality of the Duplin Formation, near Magnolia, North Carolina, USGS 23639, × 118.

*Paracytheridea rugosa* Edwards, 1944

3. Exterior view female left valve, USNM 191497, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 122.

*Paracytheridea altila* Edwards, 1944

4. Exterior view female left valve, USNM 191500, Croatan Formation, sample 13 of this study, USGS 25377, × 122.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## PLATE 29

*Paracytheridea cronini*, new species

1. Exterior view female left valve, holotype, USNM 172759, type locality of the Duplin Formation, near Magnolia, North Carolina, USGS 23639, × 113.

*Paracytheridea mucra* Edwards, 1944

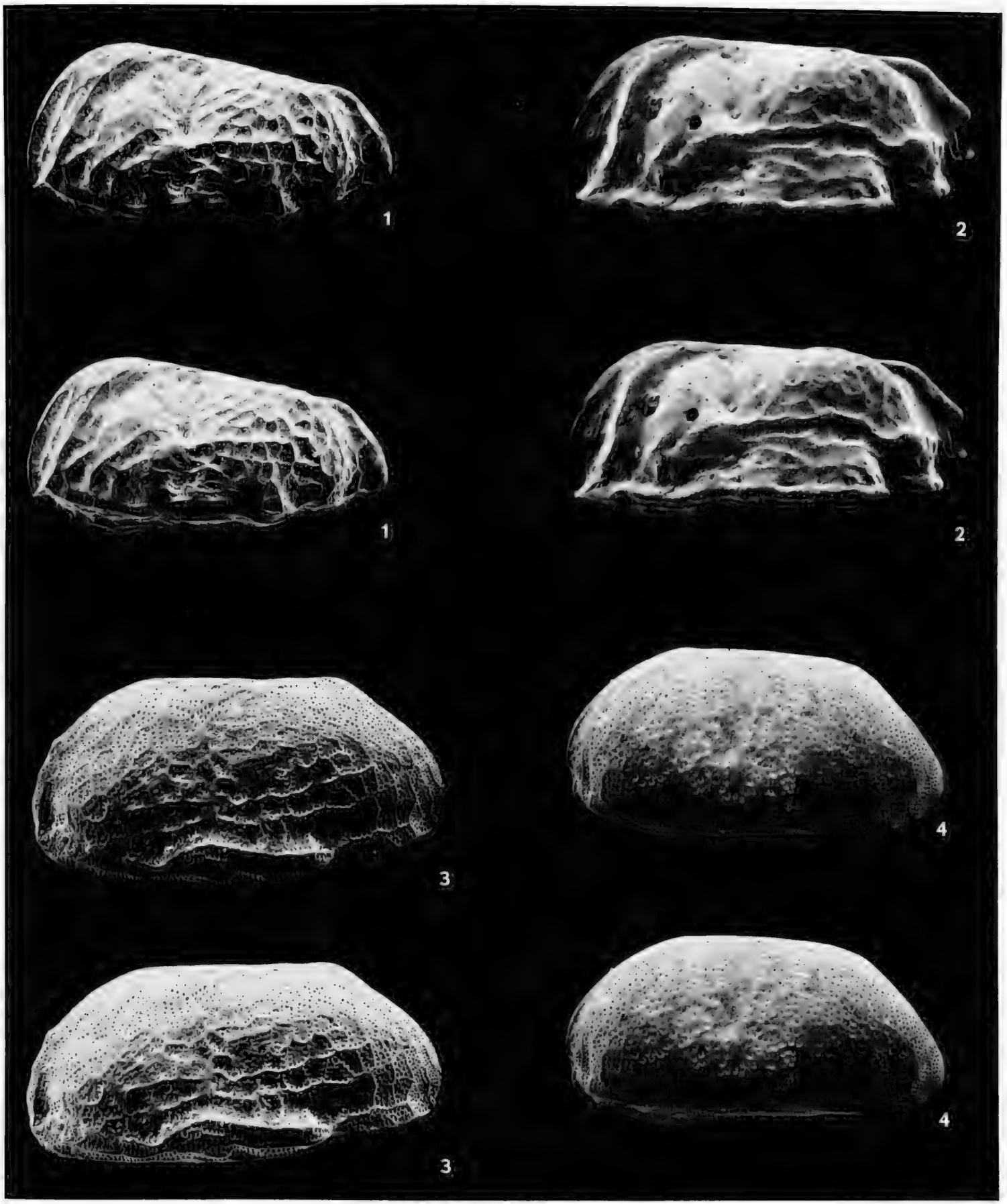
2. Exterior view female left valve, USNM 172758, Yorktown Formation, Suffolk, Virginia, sample 29 of Hazel (1971a), USGS 24814, × 102.

*Microcytherura choctawhatcheensis* (Puri, 1954)

3. Exterior view male left valve, USNM 191498, Waccamaw Formation, pit near Old Dock, North Carolina, USGS 25445, × 130.

*Microcytherura similis* (Malkin, 1953)

4. Exterior view female left valve, USNM 172751, Yorktown Formation, Nansemond County, Virginia, sample 32 of Hazel (1971a), USGS 24622, × 117.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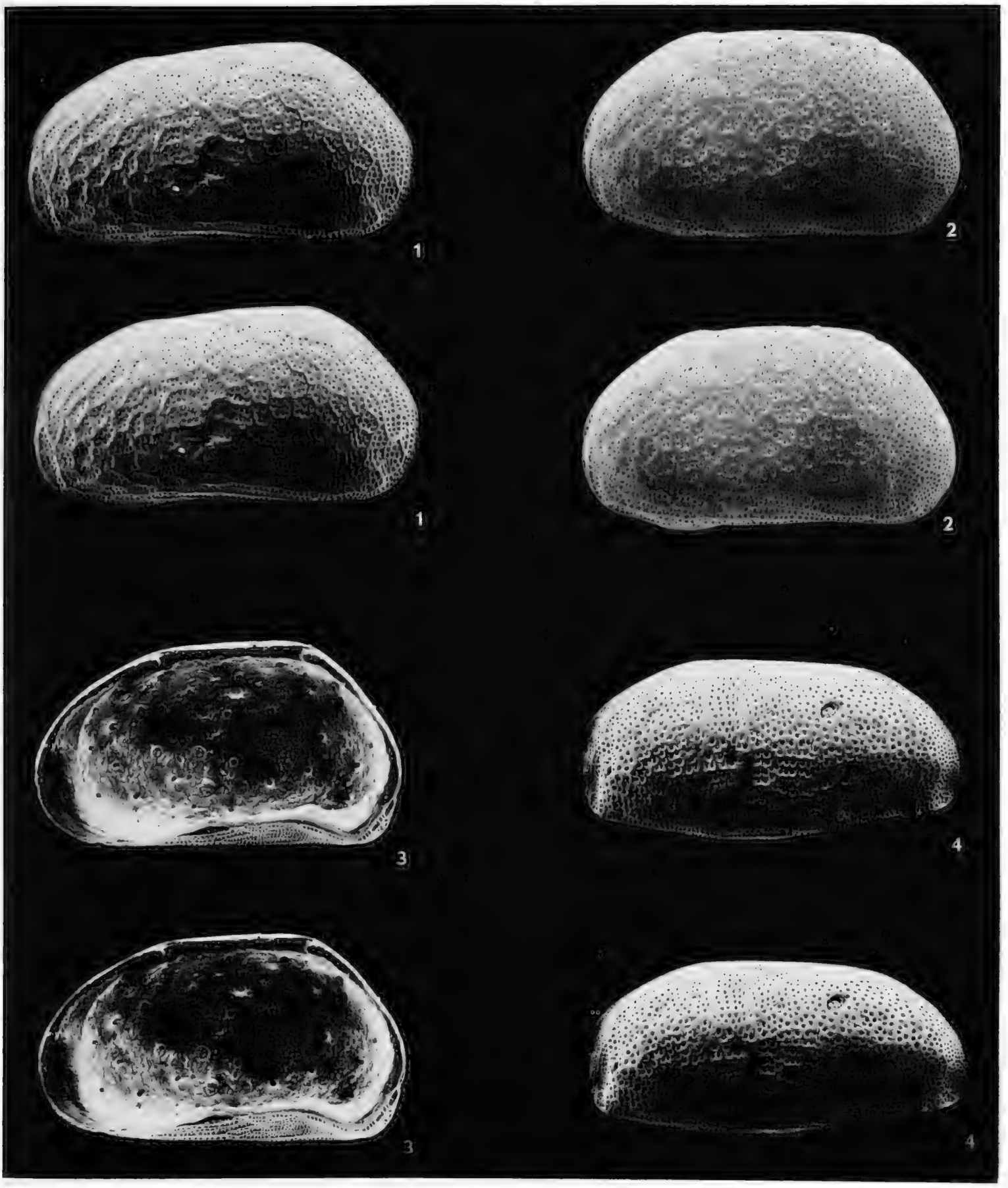
## PLATE 30

*Microcytherura expanda*, new species

1. Exterior view male left valve, USNM 191481, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 123.
2. Exterior view female left valve, holotype, USNM 172752, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 117.
3. Interior view female right valve, USNM 191482, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 20 of Hazel (1971a), USGS 24897, × 117.

*Microcytherura similis* (Malkin, 1953)

4. Exterior view male left valve, USNM 191483, Yorktown Formation, Nansemond County, Virginia, sample 32 of Hazel (1971a), USGS 24622, × 127.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## PLATE 31

*Microcytherura minuta*, new species

1. Interior view female right valve, USNM 191484, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 18 of Hazel (1971a), USGS 24895, × 135.
2. Exterior view male left valve, USNM 313690, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 18 of Hazel (1971a), USGS 24895, × 138.
3. Exterior view female left valve, holotype, USNM 172750, Yorktown Formation, Williamsburg, Virginia, sample 45 of Hazel (1971a), × 150.

*Microcytherura similis* (Malkin, 1953)

4. Interior view female right valve, USNM 313691, Yorktown Formation, Nansemond County, Virginia, sample 32 of Hazel (1971a), USGS 24622, × 154.

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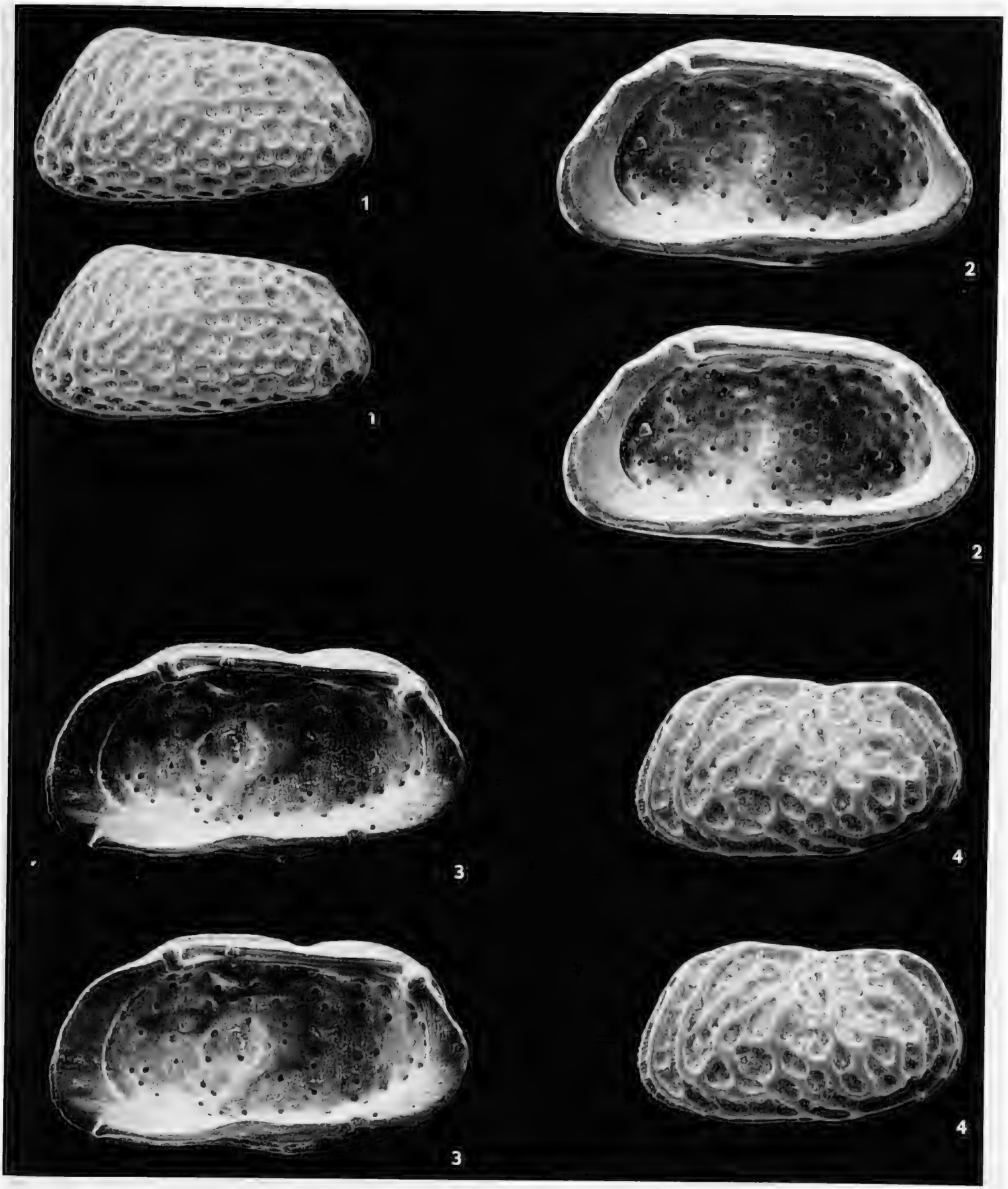
## PLATE 32

*Bensonocythere trapezoidalis* (Swain, 1974)

1. Exterior view male left valve, USNM 167395, Yorktown Formation, near Palmyra, North Carolina, sample 11 of Hazel (1971a), USGS 24889, × 90.
2. Interior view female right valve, USNM 167396, Yorktown Formation, near Palmyra, North Carolina, sample 11 of Hazel (1971a), USGS 24889, × 113.

*Bensonocythere rugosa*, new species

3. Interior view female right valve, USNM 167383, Yorktown Formation at Petersburg, Virginia, sample 38 of Hazel (1971a), USGS 24908, × 90.
4. Exterior view female left valve, holotype, USNM 167382, Yorktown Formation at Petersburg, Virginia, sample 39 of Hazel (1971a), USGS 24909, × 86.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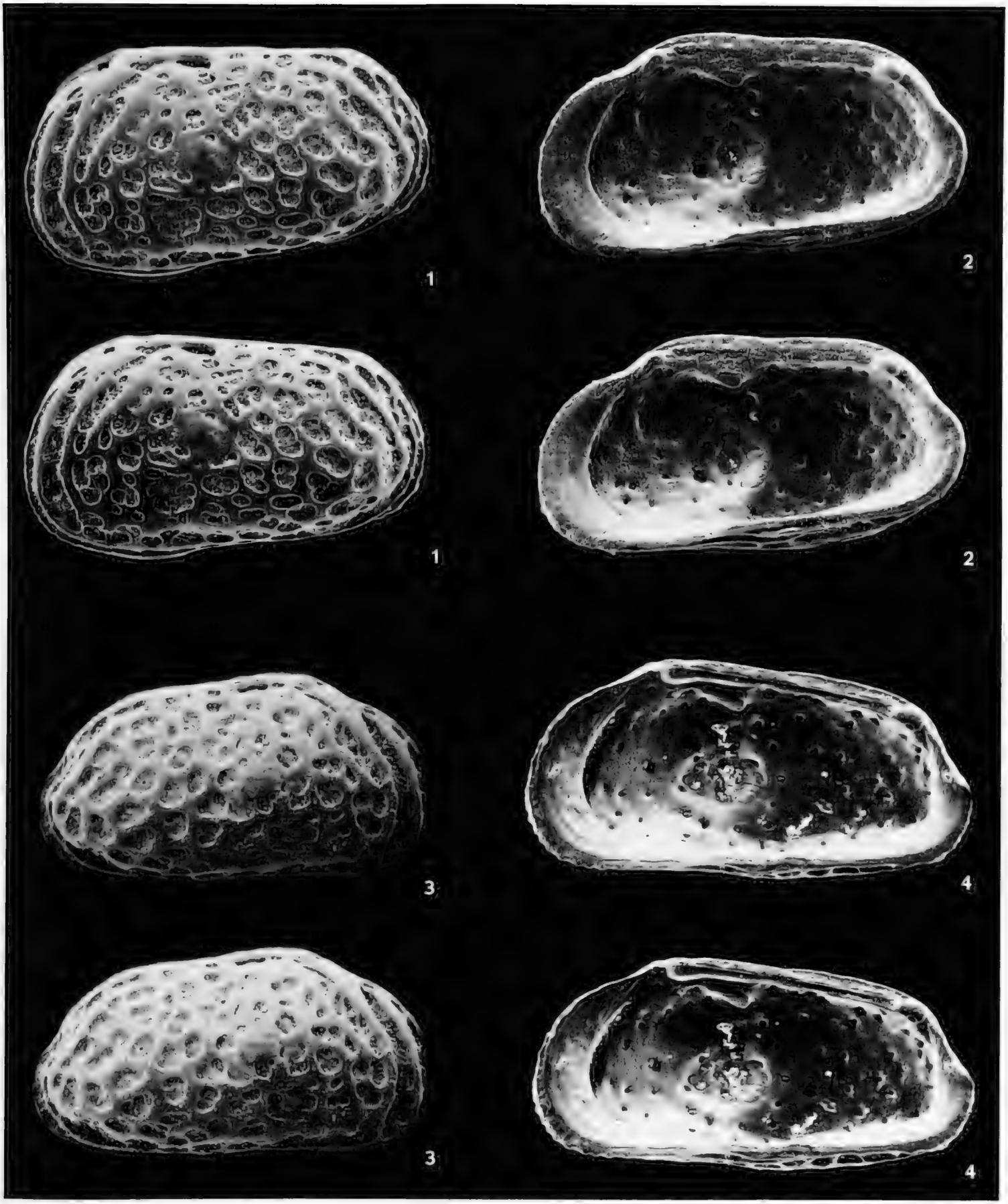
## PLATE 33

*Bensonocythere ricespitensis*, new species

1. Exterior view female left valve, holotype USNM 167394, Yorktown Formation, Hampton City, Virginia, sample 36 of Hazel (1971a), USGS 24907, × 100.
2. Interior view female right valve, USNM 167391, Yorktown Formation, Hampton City, Virginia, sample 36 of Hazel (1971a), USGS 24907, × 98.
3. Exterior view female right valve, same specimen as figure 2, × 98.
4. Interior view male right valve, USNM 191383, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 18 of Hazel (1971a), USGS 24895, × 128.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## PLATE 34

*Bensonocythere bradyi*, new species

1. Exterior view male right valve, holotype, USNM 167380, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 17 of Hazel (1971a), USGS 24894, × 78.
2. Interior view female right valve, USNM 167381, Yorktown Formation, Hampton City, Virginia, sample 37 of Hazel (1971a), USGS 24805, × 75.

*Bensonocythere gouldensis*, new species

3. Exterior view male left valve, USNM 167389, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 18 of Hazel (1971a), USGS 24895, × 90.
4. Interior view female right valve, USNM 167388, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 19 of Hazel (1971a), USGS 24896, × 95.

*Bensonocythere calverti* (Ulrich and Bassler, 1904)

5. Exterior view male left valve, USNM 167387, Yorktown Formation, near Palmyra, North Carolina, sample 11 of Hazel (1971a), USGS 24889, × 68.

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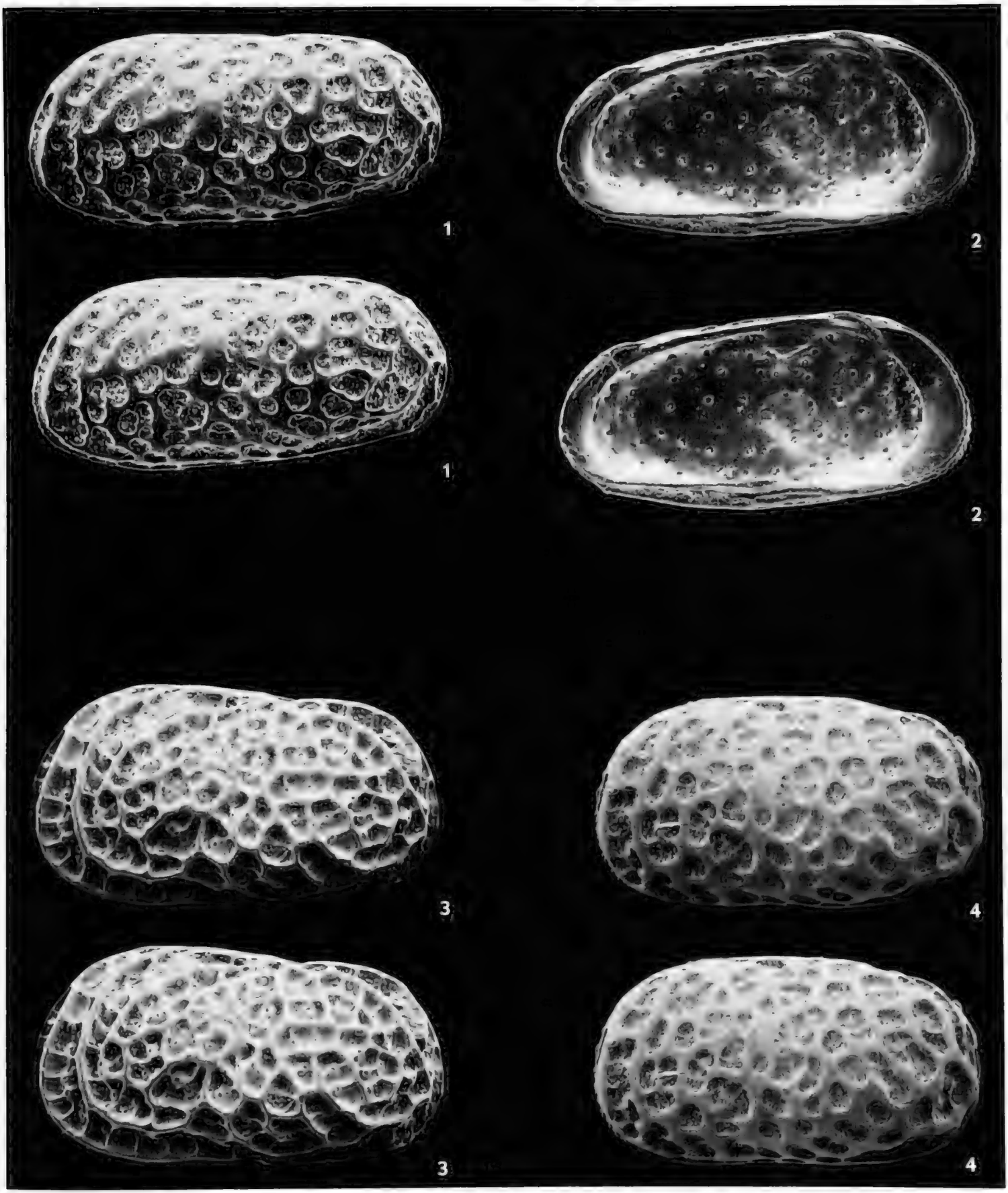
## PLATE 35

*Bensonocythere blackwelderi*, new species

1. Exterior view male left valve, USNM 191505, Yorktown Formation, Hampton City, Virginia, sample 37 of Hazel (1971a), USGS 24805, × 110.
2. Interior view male left valve, USNM 172481, Yorktown Formation, Hampton City, Virginia, sample 37 of Hazel (1971a), USGS 24805, × 110.
4. Exterior view female left valve, holotype, USNM 167398, Yorktown Formation, Isle of Wight County, Virginia, sample 33 of Hazel (1971a), USGS 24823, × 90.

*Bensonocythere whitei* (Swain, 1951)

3. Exterior view female left valve of Swain's holotype, USNM 560640, "Yorktown" Formation, Edenton Naval Air Base, North Carolina, 55 foot (16.8 m) depth in well (downdip stratigraphic equivalent of localities 3 and 4 of Hazel, 1971a), × 109.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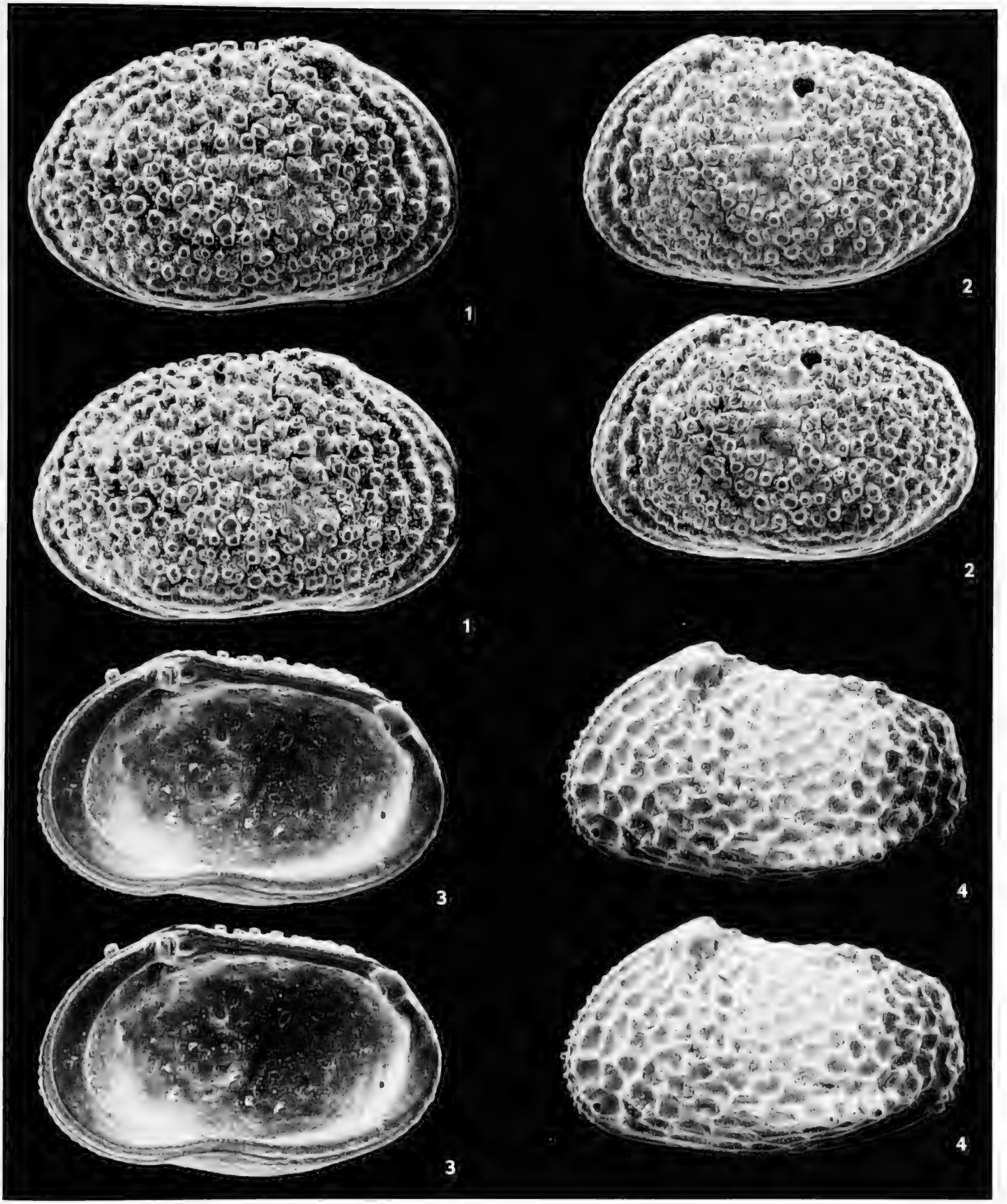
## PLATE 36

*Echinocythereis leecreekensis*, new species

1. Exterior view female right valve, holotype, USNM 191495, Croatan Formation, sample 10 of this study, USGS 25359, × 70.
2. Exterior view female left valve, USNM 191510, Croatan Formation, sample 10 of this study, USGS 25359, × 70.
3. Interior view female right valve, USNM 191508, Croatan Formation, sample 11 of this study, USGS 25376, × 77.

*Echinocythereis planibasalis* (Ulrich and Bassler, 1904)

4. Exterior view male left valve, USNM 172754, Yorktown Formation near Jamestown, Virginia, sample 41 of Hazel (1971a), USGS 24717, × 70.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## PLATE 37

*Bensonocythere rugosa*, new species

1. Exterior view male right valve, USNM 167384, Yorktown Formation, Hampton City, Virginia, sample 36 of Hazel (1971a), USGS 24907, × 118.

*Bensonocythere gouldensis*, new species

2. Exterior view female left valve, holotype, USNM 167385, "Yorktown" Formation, near Mt. Gould Landing, North Carolina, sample 19 of Hazel (1971a), USGS 24896, × 75.
3. Exterior view female left valve, USNM 167390, Yorktown Formation, Hampton City, Virginia, sample 37 of Hazel (1971a), USGS 24805, × 82.

*Bensonocythere blackwelderi*, new species

4. Exterior view female right valve, USNM 167400, Yorktown Formation, Hampton City, Virginia, sample 36 of Hazel (1971a), USGS 24907, × 112.

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## PLATE 38

*"Pontocythere"* sp. I

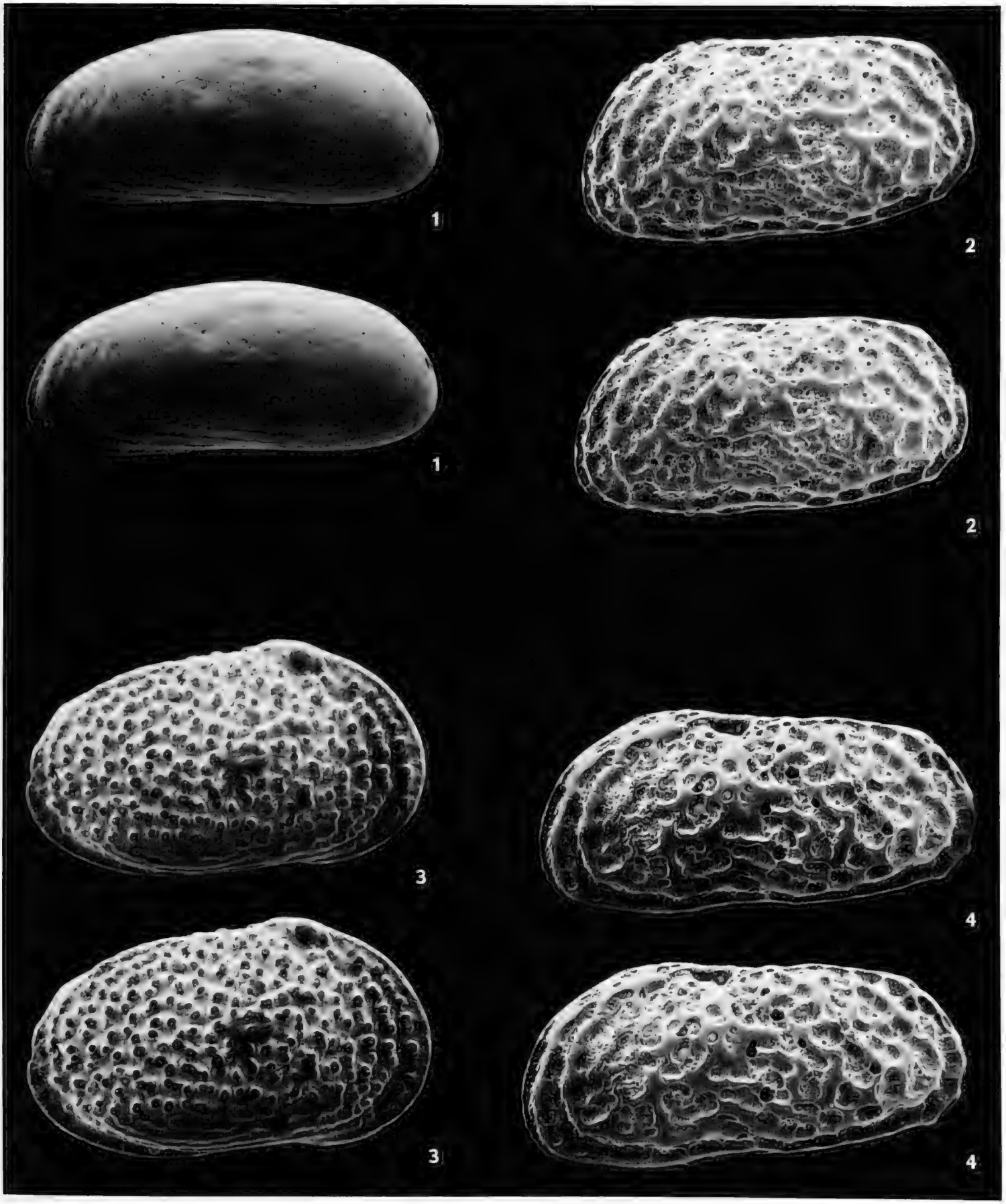
1. Exterior view female left vale, USNM 172523, Yorktown Formation, Petersburg, Virginia, sample 38 of Hazel (1971a), USGS 24908, × 90.

*Bensonocythere bradyi*, new species

2. Exterior view female left valve, USNM 191514, Yorktown Formation, Petersburg, Virginia, sample 38 of Hazel (1971a), USGS 24908, × 80.
4. Exterior view male left valve, USNM 167382, Yorktown Formation, Petersburg, Virginia, sample 38 of Hazel (1971a), USGS 24908, × 93.

*Echinocythereis leecreekensis*, new species

3. Exterior view male right valve, USNM 191509, Croatan Formation, sample 11 of this study, USGS 25376, × 70.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# The Post-Yorktown Stratigraphy and Geomorphology of the Neuse-Pamlico Area, Eastern North Carolina

*Walter H. Wheeler, Raymond B. Daniels, and Erling E. Gamble*

ABSTRACT

Regional study of the post-Yorktown history of the Neuse-Tar-Pamlico rivers area, based on limited exposures and many auger holes, reveals the buried Aurora paleoscarp on the erosional surface of the Yorktown Formation, extending from the Pamlico River at the Lee Creek Mine southward to the coast near Morehead City. Overlying the Yorktown Formation where present and the Castle Hayne Formation elsewhere in the area is a complex of pre-late Pleistocene deposits herein referred to the informal Small sequence or Croatan Formation (including the James City Formation), which includes both marine and nonmarine beds. The late Pleistocene surficial materials overlying the Small sequence are referred to the Talbot and Pamlico morphostratigraphic units (msu). The Talbot msu includes the Flanner Beach and Neuse formations. The Pamlico msu includes most of the surface sediments east of the Suffolk Scarp, locally represented by the Minnesott Ridge.

## Introduction

The Lee Creek Mine of Texasgulf Inc. is situated in the northern part of our regional study area of the Coastal Plain in the Neuse-Tar-Pamlico rivers region of eastern North Carolina. The mine lies northwest of Aurora in Beaufort County, North Carolina. Most of the data are from auger holes that give the relation between the regional geology and the section exposed at the Lee Creek Mine.

The stratigraphic column in the Lee Creek Mine is, in ascending order: Pungo River Formation, middle Miocene; Yorktown Formation, upper Miocene and/or lower Pliocene; Small sequence (which may prove to be an enlarged concept of the Croatan Formation or the James City Formation), upper Pliocene or lower Pleistocene; and the Pamlico morphostratigraphic unit, upper Pleistocene.

The Pungo River Formation is the lowest unit exposed in the mine but is not within the scope of this particular study.

The Yorktown Formation in this region consists of fossiliferous to barren marine sandy loam to silty clay. It lacks the organic zones of the overlying Small sequence and is noted for the presence of *Ecphora* and other guide fossils.

The top of the Yorktown Formation is an erosional surface that has very little relief in the areas between major streams. However, a gently sloping buried scarp, the Aurora paleoscarp, marks the top of the Yorktown Formation along a north-south trend, which happens to lie in the vicinity of the Lee Creek Mine. Immediately below the unconformity, the Yorktown Forma-

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tion is generally enriched in calcium carbonate, which may form a crust difficult to penetrate with a power auger. This is not the case at the Lee Creek Mine, however.

The Small sequence (Croatan or James City Formation) consists of sands or sandy loams, frequently very rich in marine shells alternating with organic layers. The organic layers may be as peats, as sandy loams with abundant wood chunks or fragments, or merely an organically stained sediment suggesting a paleosol. There is no pebble zone at the base of the Small sequence, but the change of lithology is distinct enough to allow identification of the boundary over a wide area. At the Lee Creek Mine the Small sequence consists of incline-bedded sands very rich in large and small marine shells that grade upward into a sparsely fossiliferous sandy loam with or without organic staining. Our regional work clearly shows that the upper highly fossiliferous layer in the Lee Creek Mine is not an upper part of the Yorktown Formation, but is a distinct and separate unit.

The Pamlico morphostratigraphic unit (msu) includes all surface sediments east of the Suffolk Scarp (with the exclusion of some Recent material). The unit is typically fine textured in the upper 3 to 5 feet (0.9 to 1.5 m) and becomes sandier toward the base. Marine fossil shells are abundant, both as a basal hash layer and as few to common shells dispersed through a sandy matrix.

The Pamlico never contains intercalated organic layers; the only organic zones are at the top of the unit. At the Lee Creek Mine the Pamlico msu consists of near-shore marine and estuarine sands and silty sands notable for a profusion of burrows and other lebensspuren of marine organisms. A prominent zone of pebbles, cobbles, and a few boulders mark the distinct unconformity at the base.

The organic rich silty sands underlying the unconformity are at the upper part of the Small sequence or Croatan Formation.

The Minnesott Ridge, a ridge of sand up to a mile wide, is associated with the inner edge of the Pamlico terrace and morphostratigraphic unit. The seaward face of the Minnesott Ridge forms part of the Suffolk Scarp. The ridge terminates at the Neuse River to the south and at a point about 4 miles (6.4 km) west of the Lee Creek Mine to the north.

ACKNOWLEDGMENTS.—Much of the material presented in this report was modified from a portion of the guidebook for the joint 1972 annual meeting of the Carolina Geological Society and the Atlantic Coastal Plain Geological Association (Daniels et al., 1972).

The authors have benefited from discussions and field trips with Dr. Edward S. Belt of Amherst College, Dr. H. Allen Curran of Smith College, Dr. William A. White of the University of North Carolina at Chapel Hill, Dr. Clayton Ray of the National Museum of Natural History, Smithsonian Institution, Dr. Frank C. Whitmore, Jr., of the U.S. Geological Survey and Dr. C. Stephen Holzhey of the Soil Conservation Service, U.S. Department of Agriculture, Beltsville, Maryland. An earlier version of the manuscript was reviewed by Frank C. Whitmore, Jr., Druid Wilson, and the late Louis Ray.

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## Stratigraphic Nomenclature

The unconsolidated Neogene deposits of the Atlantic Coastal Plain are very similar to each other, and their interpretation is difficult enough for the uninitiated worker without turning him loose into an unfamiliar terminological jungle. Accordingly, we have chosen to circumvent some of these difficulties by assigning to the three stratigraphic units that we discuss names that do not imply more knowledge of their genesis than we have.

The provisional and informal name, Small sequence (Daniels et al., 1972), is applied to the older Pleistocene (or possibly Pliocene) unit immediately overlying the Yorktown Formation in

the study area (Figure 1). The Small sequence is in part the marine James City Formation of DuBar and Solliday (1963) but includes nonmarine beds. The name, "Croatan Formation," proposed by Dall (1892) and redefined by Mansfield (1928) may prove to be most useful (Fallaw and Wheeler, 1969).

The surficial materials underlying the Talbot and the Pamlico surfaces but overlying the Small sequence are referred to as the Talbot and the Pamlico morphostratigraphic units respectively. The term "morphostratigraphic unit" is applied to surficial deposits in the Coastal Plain because, as Frye and Willman (1960:7–8) state in their original discussion, "they are identifiable by their form and not their lithology, which in many cases . . . is not distinguishable from one . to the next, they are not normal rock-stratigraphic units." To quote further for clarification: "A morphostratigraphic unit is defined as comprising a body of rock that is identified primarily from the surface form it displays; it may or may not be distinctive lithologically from contiguous units; it may or may not transgress time through its extent." Frye and Willman (1962) in a later discussion of this idea indicated that the term could be applied to fluvial terraces and other nonmarine stratigraphic and geomorphic elements. We would like to extend the term morphostratigraphic unit (hereafter abbreviated to "msu") to include marine sediments and associated surfaces, much as Thom (1967:48) has done in South Carolina. The term "msu" is preferred to "terrace" or "formation" (cf. Johnson, 1906; Cooke, 1937), because a terrace is a surface and a formation is a mappable lithologic unit. Many of the Coastal Plain surficial sediments do not fit the definition of a formation, but the term "morphostratigraphic unit" can easily be applied to these elements without violating sound stratigraphic principles. The use of morphostratigraphic unit does not preclude the application of formational names if they are defined under the rules of formal lithostratigraphic nomenclature.

Since the body of this paper was written, our subsequent work has made us more inclined to regard the "Croatan Formation" as a valid and available name for the post-Yorktown but prelate Pleistocene sediments of the Neuse-Pamlico area. Under this interpretation the provisional, informal name of "Small sequence" is a junior synonym of Croatan (Wheeler, Daniels, and Gamble, 1979).

The Croatan Formation is distinguishable lithologically and stratigraphically in its type area along the south bank of the Neuse River between Cherry Point Marine Air Station and Flanner Beach. These outcrops lie approximately 31 miles (50 km) south of the Lee Creek Mine. Lithologic continuity is shown in auger samples from Lee Creek Mine to the north bank of the Neuse River. The Croatan Formation consists mainly of silty sands and sands that are very fossiliferous at several localities. One of the most fossiliferous of these Croatan localities is the Lee Creek Mine. In addition, there is generally a nonmarine organic zone or zones near the top of the formation. These organic zones range from a thin buried soil to layers rich in peaty fine sands or clays. Some of these zones contain large masses of wood, such as the cypress stumps at Flanner Beach.

Dall (1892:209) named the Croatan Formation for two outcrops, one by the mouth of Slocum's Creek, on what is now the Cherry Point Marine Air Station, and the other at a beach about 2 miles (3.2 km) to the west. He noted that there was "ferruginous sandy clay, 10 to 12 feet [3 to 3.7 m]" at the top with "bluish clay with fossils (Pliocene), 5 to 6 feet [1.5 to 1.8 m]" under that. He differentiated the lower clay as "Pliocene" and noted its distinct lithology. Dall did not, however, explicitly place the top of the Croatan Formation at the top of the "blue clay." On the other hand, Mansfield (1928:135) noted that the fossil collections studied by Dall came from both Croatan and post-Croatan units at this locality. Mansfield proposed to clarify the matter by restricting the name "Croatan" to the lower or "Pliocene" part. He also noted an unconformity at the top of the Croatan Formation, as thus defined. This disconformity may be seen at Dall's western locality along the shoreline of the Neuse

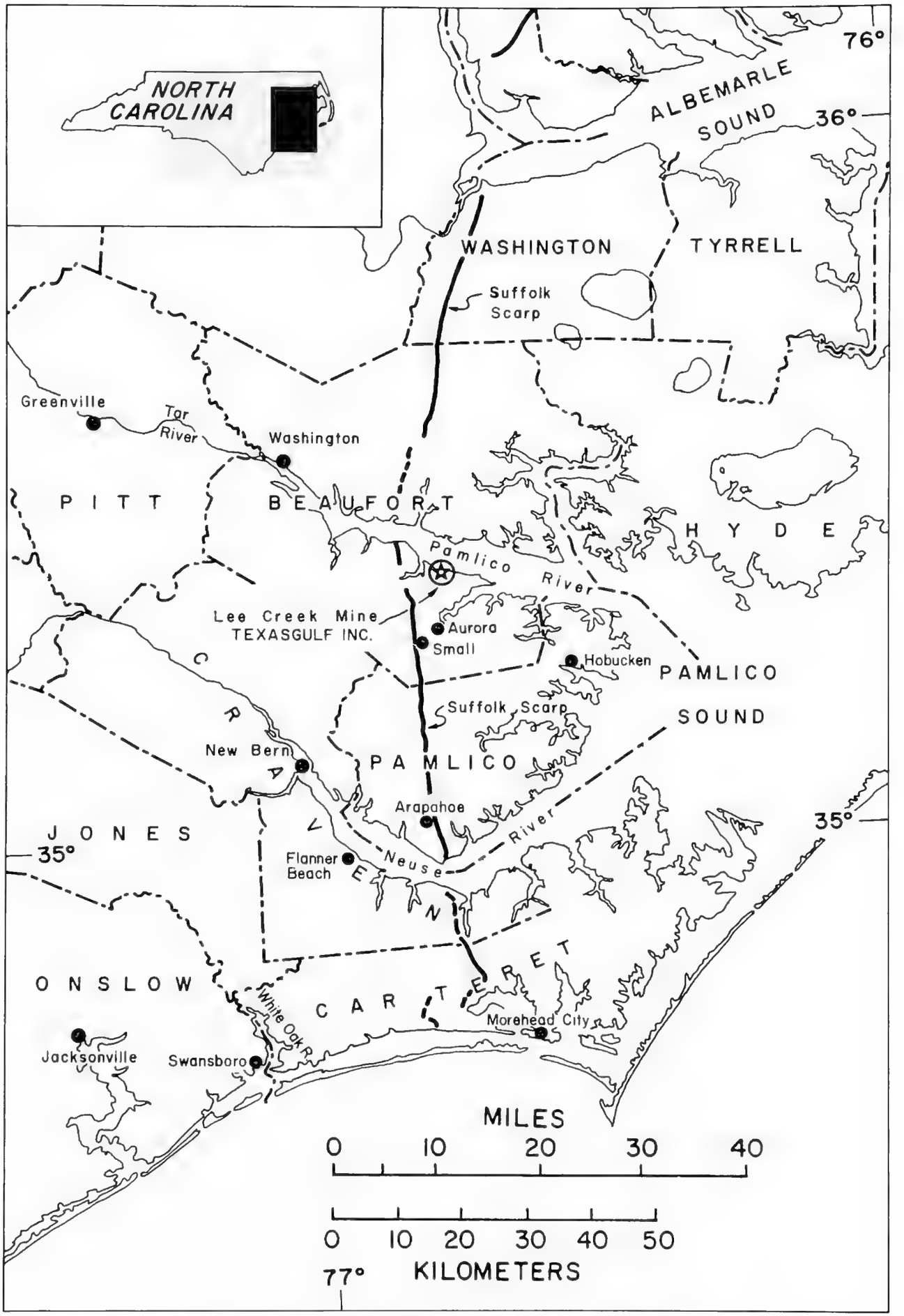


FIGURE 1—Location of study area in eastern North Carolina.

estuary at or just below the water line. Many fossil colonial corals can be seen there, whereas corals are rare in the overlying Flanner Beach Formation.The name "Croatan Formation" as defined (however poorly) by Dall and redefined clearly by Mansfield is therefore, a valid and available name, and the James City Formation of DuBar and Solliday (1963) must then be considered a junior synonym, if applied to the entire Croatan Formation. Snyder and Hine (pers. comm.) regard the James City as a member of the Croatan Formation.

Mixon and Pilkey (1976:9) regard the Croatan, as we have used it, as

> not a valid geologic unit, in either lithostratigraphic or biostratigraphic sense, inasmuch as it lumps dissimilar stratigraphic units such as the marine James City Formation of DuBar and Solliday (1963) (Pliocene?), the cypress stump bed at Flanner Beach and other swamp deposits (Pleistocene), and fossiliferous marine beds in the area of the Texasgulf Sulphur phosphate mine which appear to have been assigned to the Yorktown Formation (Miocene and Pliocene) by other workers.

The generalized stratigraphic sequence in the study area is shown in Figure 2.

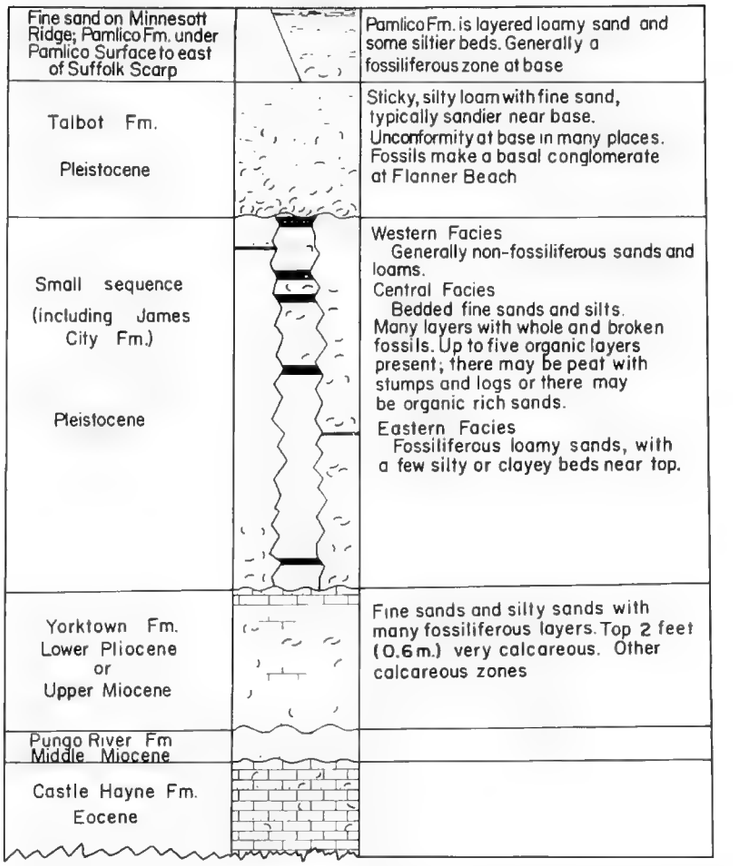


FIGURE 2.—Generalized and composite stratigraphic column between Swansboro (east of Jacksonville) and the Lee Creek Mine. (Small sequence = Croatan Formation.)

## YORKTOWN FORMATION

The Yorktown Formation is regarded as upper Miocene or lower Pliocene or both. In this region it consists dominantly of fossiliferous to barren marine fine sand and loam, silty sand and silty clay. There are many layers and lenses with abundant to few marine fossils.

There is a distinct erosional surface at the contact of the Yorktown Formation with the overlying Small sequence (= Croatan Formation). The uppermost Yorktown beds immediately below this unconformity were apparently enriched in calcium carbonate, resulting in either a highly calcareous and compact very light green loam or a partially indurated material. This calcareous zone is widespread through the area, but happens to be missing at the Lee Creek Mine.

THE AURORA PALEOSCARP.—Contours on the top of the Yorktown Formation reveal a very gentle, buried scarp that trends north-south across our study area (Figure 3). It goes from the north bank of the Pamlico River at the Lee Creek Mine south to the coast near Morehead City. The Lee Creek Mine is on the trend of this feature, the scarp slopes 40 feet (12.2 m) in 3.5 miles (5.6 km) or about 11 feet (3.4 m) per mile (1.6 km) (Figure 3). This seemingly insignificant slope in the present interfluve areas contrasts strongly with the general slope of the post-Yorktown unconformity of 1 foot (0.3 m) per mile (1.6 km) to the west of the scarp and 3 feet (0.9 m) per mile (1.6 km) to the east. The Pamlico estuary is cut deeply into the Yorktown Formation (Welby, 1971).

Our contours at the top of the Yorktown Formation along the Aurora paleoscarp match very well with those of Welby along this portion of the Pamlico River (Welby, 1971, fig. 2). Welby's data were mainly from a High Resolution Boomer survey made from a boat on the Pamlico and Pungo rivers. As a consequence, his contour lines

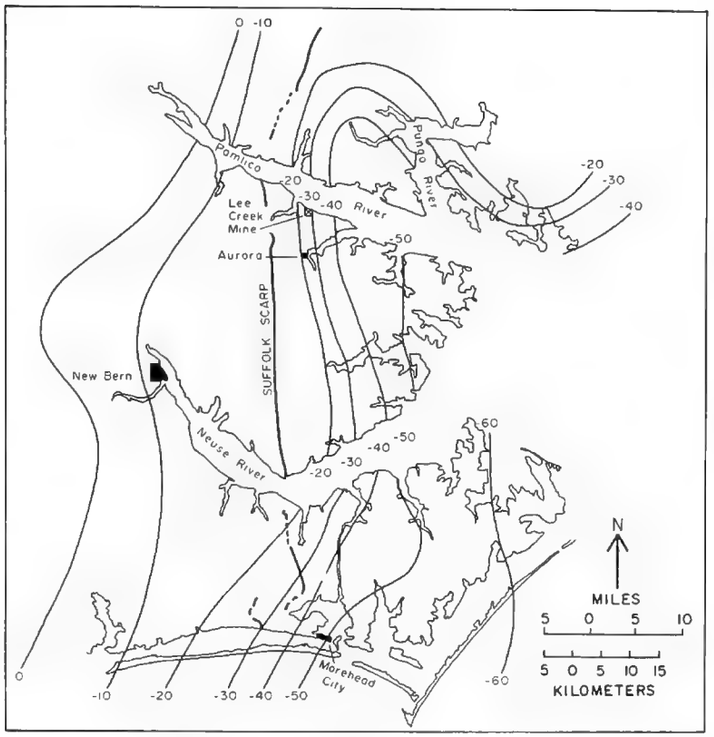


FIGURE 3.—Structure contour map on top of Yorktown Formation between the Pamlico River and Morehead City, North Carolina. (Elevations in feet below mean sea level.)

barely extend onto land areas. Nevertheless, the Aurora paleoscarp may be seen clearly on his map, with the position of the Lee Creek Mine marked at its crest. The present day Pamlico estuary is cut into sediments that were previously laid down in stream channels and irregular depressions, which were previously cut in Pliocene-Pleistocene time into the upper portion of the Yorktown Formation (Welby, 1971:201–203). The smoothness of the unconformity as mapped is somewhat misleading because our auger holes are a mile or more apart. Additional detail will undoubtedly show that the scarp is much more irregular than shown in Figure 3, because the relief at the top of the Yorktown locally may reach 30 feet (9.1 m). However, we feel that the major outlines of the scarp are reasonably well established.

The boundary between crustal segment F and crustal segment G of Brown, Miller, and Swain (1972) passes through this area with a north-south trend. The boundary between these two segments is a hinge zone. This hinge zone has been cited by Miller (1971:35–41) as part of the mechanism for forming the restricted, shallow water marine basin in which the middle Miocene Pungo River Formation was deposited.

No cause and effect relationship is claimed for the association of the Suffolk Scarp and Aurora paleoscarp, the crustal segment boundary of Brown, Miller, and Swain (1972), or the hinge near the western boundary of the Pungo River Formation (Miller, 1971). Nevertheless, this striking juxtaposition deserves to be kept in mind as more data are produced.

## SMALL SEQUENCE

(= Croatan Formation)

Overlying the Castle Hayne or the Yorktown formations in the area studied (Figures 4, 5) is a

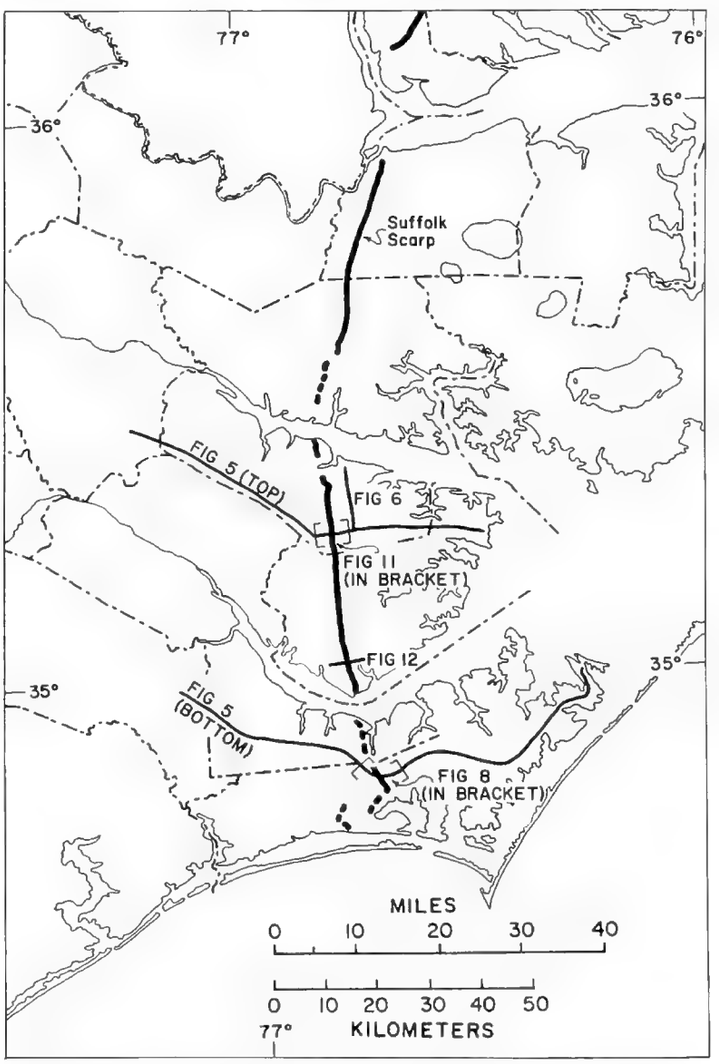


FIGURE 4.—Location of sections of Figures 5, 6, 8, 11, and 12.

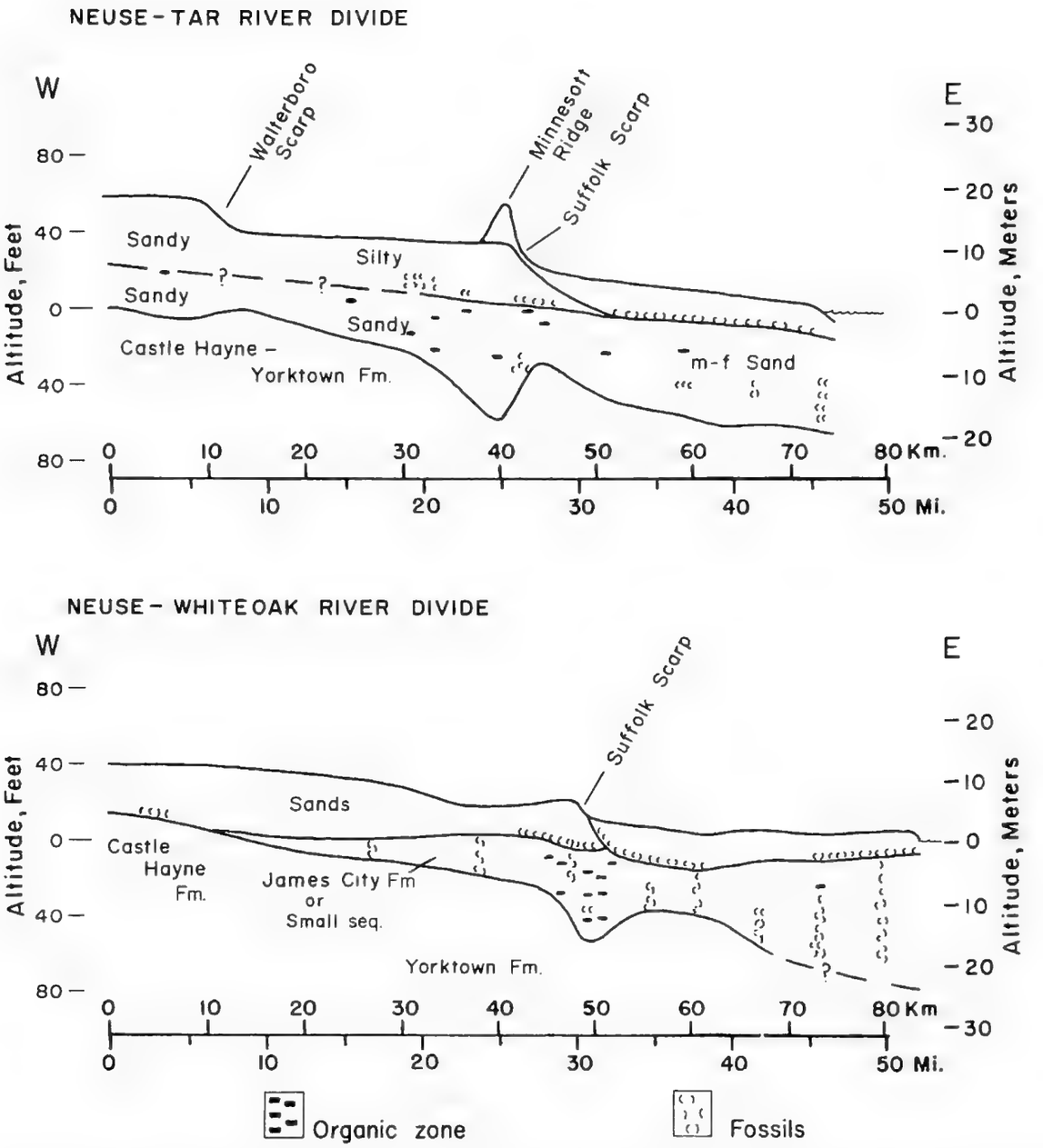


FIGURE 5.—Generalized west to east relations of Small sequence to overlying and underlying sediment. (The broken lines with question marks indicate uncertain boundaries; m-f Sand indicates medium-fine sand.)

complex of beds called the Small sequence. This proposed name is derived from the community of Small in Beaufort County where the sequence was first recognized in a series of auger holes. The Small sequence includes all strata between the Yorktown Formation, or the Castle Hayne Formation where the Yorktown is absent, and the overlying surficial sediments. It does not include the overlying Flanner Beach Formation of DuBar and Solliday (1963) or the Neuse Formation of Fallaw and Wheeler (1969), both of which are part of the Talbot msu. The Small sequence is a complex of interbedded clays to sands with one or more organic horizons. (An organic horizon may be an A-1 horizon of a buried soil, a peaty or mucky sand, or even a pure peat or muck; Daniels, Gamble, and Wheeler, 1972.) The Small sequence includes the fossiliferous James City Formation, a nonfossiliferous facies north of New Bern, which seems to occupy the same stratigraphic position as the James City Formation and a fossiliferous sand and nonfossiliferous sand

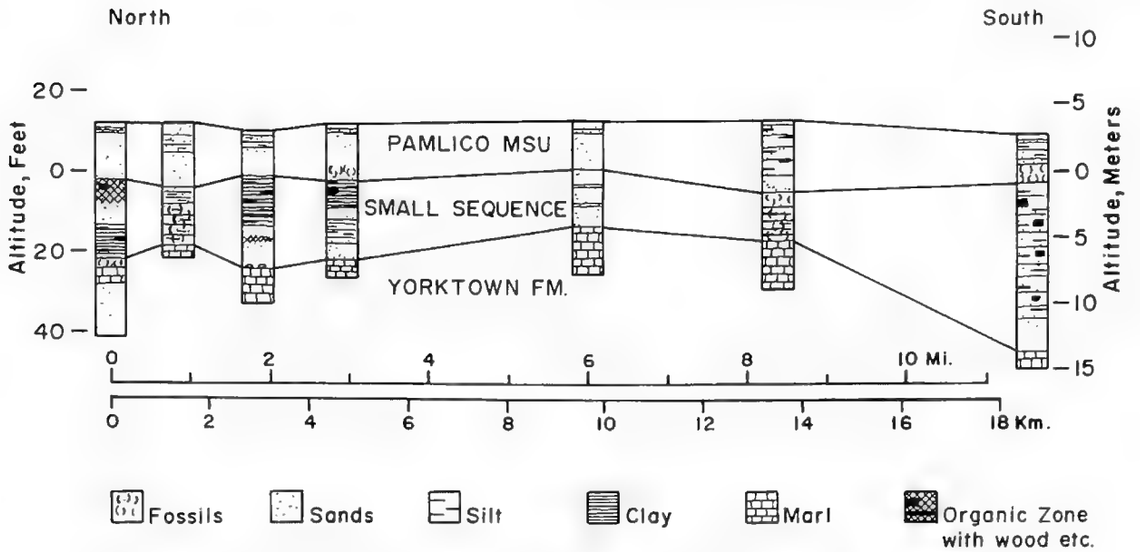


FIGURE 6.—North-south traverse from Lee Creek Mine to west-east traverse of Neuse-Tar divide. (Small sequence = Croatan Formation.)

to clay unit east of the Suffolk Scarp. Further work is needed to clarify whether or not the Small and the James City are or are not synonymous. Oaks and Coch (1973:56) regard the James City Formation as a "possible equivalent of the Sedley Formation of southeastern Virginia."

A 45-mile (72-km) traverse across the Talbot and Pamlico surfaces north of the Neuse-Tar divide (Figure 5) shows the division of the Small sequence into three facies. The Small sequence is largely nonfossiliferous sands in the western facies. These nonfossiliferous sands interfinger toward the east in the vicinity of the Suffolk Scarp with sands to clays that have one or more organic horizons. Farther east the multiple organic horizons are replaced by the eastern facies composed of fossiliferous sands, although the upper part of the section may contain silts to clays and occasional thin organic units. The sequence is sharply separated from the underlying Yorktown by the distinct changes in lithology and a distinct disconformity that is traceable over large areas of eastern North Carolina (Welby, 1971). The contact with the overlying Talbot msu is questionable in the western part of the traverse, but near the Minnesott Ridge the contact is distinct. The sediments exposed at the Lee Creek Mine have been traced south to connect with the 45-mile (72-km) traverse just east of the Minnesott Ridge (Figures 4, 6).

In a traverse along the Neuse-White Oak river divide, the three facies of the Small sequence are similar to those found in the Neuse-Tar divide traverse (Figure 5). The fossiliferous facies occurring west of the multiple horizons is the James City Formation. In the Neuse-Tar traverse the multiple organics occupy an area a few miles wide, but they apparently are limited to a very narrow band between the Neuse and White Oak rivers. In both cross-sections (Figure 5), the organics occur in the immediate vicinity of the Suffolk Scarp, but this probably is a coincidence because organics occur over an area about 20 to 25 miles (32 to 40 km) wide between the Neuse and Pamlico estuaries (Figure 7). In both traverses (Figure 5) the Small sequence thickens considerably toward the east.

The following section with multiple organic horizons in the Small sequence was described from an auger hole located on Beaufort County Road 1931, 0.5 mi (0.8 km) west of its junction with county road 1927; altitude 34.2 feet (10.4 m) (Figure 7: locality 1). Munsell color designations (indicated in parentheses) are used in the descriptions. The boundary with the underlying bed is described as abrupt (<1 inch; 2.5 cm), clear (1–2 inches; 2.5–5.1 cm), or gradual (2–5 inches; 5.1–12.7 cm).

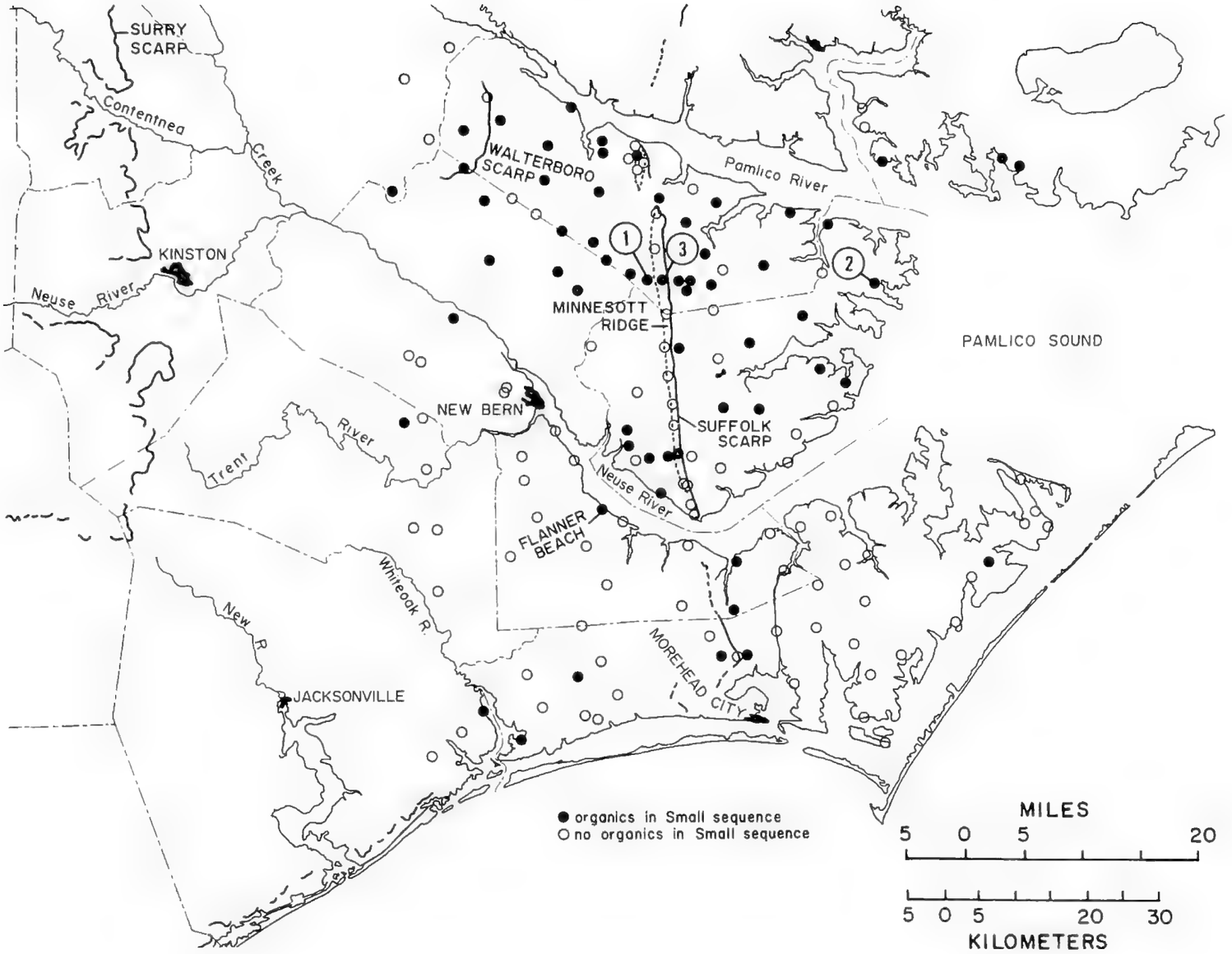


FIGURE 7.—Location of bore holes. (Localities 1–3 are discussed in detail in the text.)

| *Depth in feet (meters)* | *Description* |
|---|---|
| 0 to 0.5 (0 to 0.2) | Road fill |
| | TALBOT MORPHOSTRATIGRAPHIC UNIT |
| 0.5 to 5 (0.2 to 1.5) | Sandy loam to loamy sand. Soil profile in the Talbot msu |
| 5 to 7 (1.5 to 2.1) | Pale yellow (5Y 7/3) to light gray (2.5Y 7/2) fine sand; abrupt transition to |
| 7 to 11.5 (2.1 to 3.5) | Greenish gray (5GY 5/1) sticky silt loam grading downward to dark greenish gray (5GY 4/1) loamy fine sand at 8.5 ft (2.6 m); clear to |
| 11.5 to 13.5 (3.5 to 4.1) | Yellow (10YR 7/6) medium fine to fine sand; gradual to |
| 13.5 to 21.5 (4.1 to 6.6) | Greenish gray (5GY 6/1 to 5/1) medium fine to fine sand to loamy sand; lower 2 ft (0.6 m) are sticky loam; base of Talbot abrupt to Small sequence. |
| | SMALL SEQUENCE (= Croatan Formation) |
| 21.5 to 24 (6.6 to 7.3) | Darker than very dark brown (10YR 2/2) organic clay loam; contains wood fragments up to 2 in (5.1 cm) long; gradual to |
| 24 to 26 (7.3 to 7.9) | Darker than very dark brown (10YR 2/2) fine loamy sand to sandy loam; gradual to |
| 26 to 31.5 (7.9 to 9.6) | Gray (5Y 5/1) medium fine loamy sand with bodies of very dark grayish brown (10 YR 5/3); abrupt to |

| | |
|---|---|
| 31.5 to 38.5 (9.6 to 11.7) | Greenish gray (GY 5/1) medium fine loamy sand becoming greener than dark greenish gray (5GY 4/1) at 36 ft (11m); abrupt to |
| 38.5 to 49 (11.7 to 14.9) | Greenish gray (5GY 5/1) medium fine sand grading to medium coarse sand at 49 ft (14.9 m); abrupt to |
| 49 to 58 (14.9 to 17.7) | Dark greenish gray (5GY 4/1) stiff sticky clay to fine clay loam; clear to |
| 58 to 63.5 (17.7 to 19.4) | Dark gray (10 YR 4/1) medium sandy clay loam; common to many wood fragments 0.5 in (1.3 cm) in diameter or less; clear to |
| 63.5 to 66.5 (19.4 to 20.3) | Dark gray (10YR 4/1) sticky silty clay with few to common wood fragments; abrupt to |
| 66.5 to 74 (20.3 to 22.5) | Black (5YR 2/1) peaty sticky silty clay loam, common small (less than 0.5 in; 1.3 cm) wood fragments, abrupt to |
| 74 to 78.5 (22.5 to 23.9) | Dark gray (10YR 4/1) sticky silty clay; gradual to |
| 78.5 to 89 (23.9 to 27.1) | Dark greenish gray (5GY 4/1) silty clay loam grading to medium fine sandy clay loam at 81 ft (24.7 m); sands become fine to very fine at 86 ft (26.2 m); clear to abrupt to |
| 89 to 91 (27.1 to 27.7) | Dark gray (5Y 4/1) fine sandy clay loam with few to common darker bodies of disseminated organic matter; base of Small sequence; abrupt to |
| | YORKTOWN FORMATION |
| 91 to 98.5 (27.7 to 30.0) | Dark greenish gray (10GY 4/1) medium coarse sandy clay loam grading to light olive gray (5Y 6/2) "marl" with some material partially cemented by carbonate; Yorktown Formation; base of hole at 98.5 ft (30.0 m). |

Some of the variation of the Small sequence in its eastern distribution is given in the following section, which was described from an auger hole located approximately 2 miles (3.2 km) east of Hobucken on Pamlico County Road 1228, 1.75 miles (2.8 km) beyond end of pavement and 0.1 mile (0.2 km) from end of road (Figure 7: locality 2). Altitude 3 feet (0.9 m).

| *Depth in feet (meters)* | *Description* |
|---|---|
| 0 to 1 (0 to 0.3) | Road fill |
| | PAMLICO MORPHOSTRATIGRAPHIC UNIT |
| 1 to 5.5 (0.3 to 1.7) | Sandy clay loam soil profile in Pamlico msu; gradual to |
| 5.5 to 10 (1.7 to 3.0) | Pale olive to olive (5Y 6/3 to 5/3) medium sand interbedded with minor strata of fine sand; grades to gray (5Y 5/1) medium sand with minor strata of fine sand to loamy sand at 8.5 ft (2.6 m); clear to |
| 10 to 18 (3.0 to 5.5) | Olive gray (5Y 4/2) fine sandy clay loam interbedded with fine sandy loam and medium sand; base of Pamlico; abrupt to |
| | SMALL SEQUENCE (= Croatan Formation) |
| 18 to 27 (5.5 to 8.2) | Greenish gray (5GY 5/1) sandy clay loam interbedded with medium loamy sand to sand; abrupt to |
| 27 to 28 (8.2 to 8.5) | Dark olive gray (5Y 3/2) micaceous organic-rich silty clay that darkens on exposure; clear to |
| 28 to 31.5 (8.5 to 9.6) | Greenish gray (5GY 5/1) loam sand to medium sand interbedded with thin strata of more clayey material; abrupt to |
| 31.5 to 57 (9.6 to 17.4) | Bluish gray (5B 6/1) "marl"; coarse and medium sand with abundant shells; highly calcareous; grades to greenish gray (5GY 67/1) at 40 ft (12.2 m); clear to |
| 57 to 66 (17.4 to 20.1) | Greenish gray (5GY 5/1) sticky silty clay loam; calcareous; base of Small sequence; abrupt to |
| | YORKTOWN FORMATION |
| 66 to 68.5 (20.1 to 20.9) | Bluish gray (5B 6/1) slightly sticky hard drilling clay loam marl; probably Yorktown Formation; base of hole 68.5 ft (20.9 m) |

A series of 12 drill holes in a 4-mile (6.4-km) traverse across the Suffolk Scarp clearly shows the discontinuous nature of the organic horizons and the associated beds (Figures 4, 8). Nodular or slightly indurated limestone at the top of the Yorktown is removed in places and the relief of the erosion surface is about 30 feet (9 m). The base of the Small sequence in the western part of the traverse is fossiliferous sands (James City?) grading upward into fossiliferous and nonfossiliferous silty beds. Near the Suffolk Scarp is a complex sequence of fossiliferous and nonfossiliferous silty beds with intercalated but horizontally discontinuous organic-rich beds, which contain bald cypress wood (A.C. Barefoot, pers. comm.). Many of these organic horizons with cypress wood are at 20 to 50 feet (6.1 to 15.2 meters) below sea level. Fossiliferous marine sands and nonfossiliferous sands of probable marine

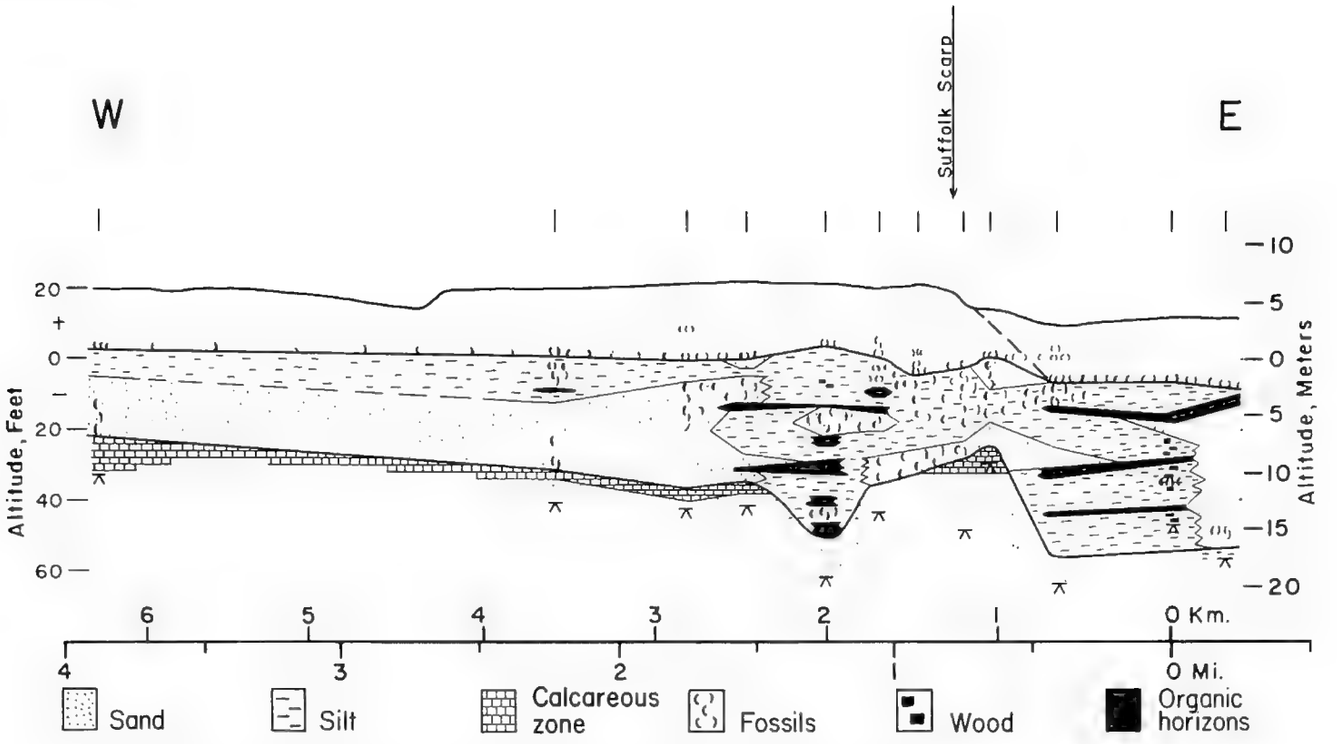


FIGURE 8.—West to east cross-section across Suffolk Scarp near Harlow Creek south of the Neuse estuary near the Craven-Carteret county line. (Location of auger holes is indicated by short vertical lines across top of figure, and their bottoms by short horizonal lines over inverted V's.)

origin also are found interbedded with the silts to silty clays. The organic horizons and associated silty beds pinch out to the east and interfinger with fine to medium sands.

A detailed section shows the complex vertical changes in sediments of the Small sequence (Figure 9). Some of the silty beds are extremely soft and semifluid and are very similar to the sediments in the modern salt marshes at the mouth of the Cape Fear River. This suggests that these soft, semifluid beds have never been dried. Yet within the same section there can be extremely tough dense clays separated by organic horizons. The tough clays, if deposited in a salt-water environment, must have been dried or de-watered sometime during their history. The organic zones and the cypress wood indicate at least short periods during which vegetation was growing in a swamp or brackish water marsh.

The relation between the buried organic horizons and the surficial Talbot msu is well illustrated at Flanner Beach on the south side of the Neuse estuary. The base of the section is a gray

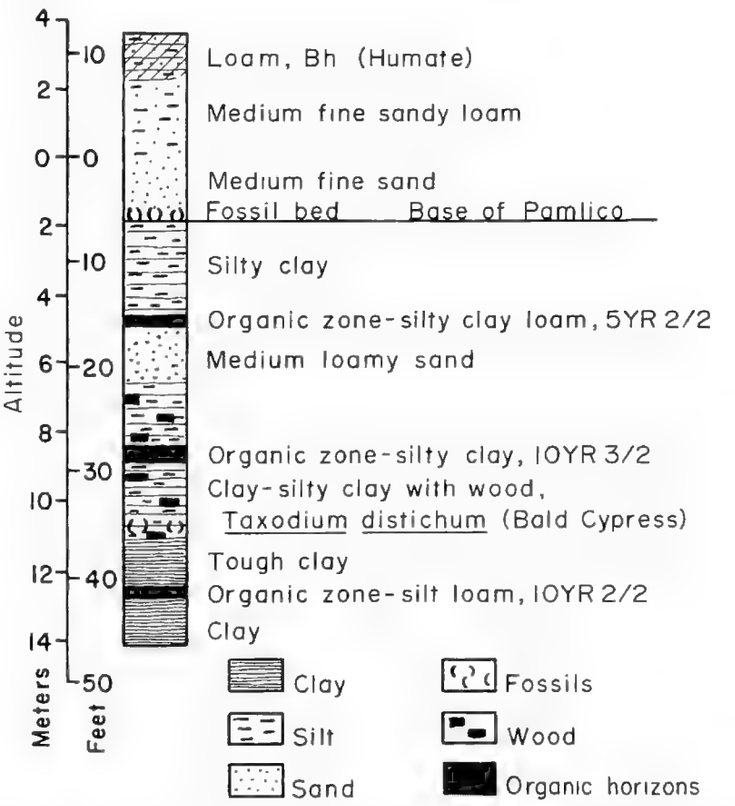


FIGURE 9.—Small sequence near Harlow Creek showing complex vertical changes in sediments. This hole is at 0 miles in Figure 8.

to olive brown clay exposed about 2 feet (0.6 m) above the estuary. The organic horizon at the top of the clay (Figures 4, 10) is truncated by a *Dinocardium* layer at the base of the overlying Talbot. At places logs or roots are imbedded in the clay but buried by the *Dinocardium* layer. The clay is without marine fossils in the exposed section, but fossils do occur in four nearby drill holes. There apparently was some weathering of the clay, as shown by the organic carbon and oxidation of iron, before the overlying Talbot msu was deposited.

Depositional Environment.—Our studies of fossils contained within the Small sequence are far from complete, but some speculation about depositional environments can be made. There seems to be a distinct possibility that the relatively clean fossiliferous sands in the eastern part of the Small sequence represent fully marine conditions. There are no or few muds and organic horizons within the sands that can be interpreted as estuary or lagoon facies. An upper clayey part occurs in about one-half of the bore holes, and these may represent localized lagoonal conditions.

The organic horizons of the Small sequence indicate that the sediments had to be exposed to subaerial conditions for a few hundred years to develop relatively thick organic layers and allow cypress stumps 6 feet (1.8 m) or more in diameter to develop (Flanner Beach section, Figure 10). The presence of marine shells intercalated with organic debris in other sections suggests that these organic layers formed very close to sea level. The relatively restricted horizontal area occupied by multiple organic layers suggests that the fluctuating marine, lagoon-like, and subaerial conditions remained in about the same geographic location throughout the deposition of 20 to 40 feet (6 to 12 m) of sediment. There appears to be little evidence that these conditions shifted westward as sea level rose.

The origin of the nonfossiliferous sands of the western facies of the Small sequence is open to considerable question. We are not sure whether these sands interfinger with the James City Formation farther to the south or whether they represent a leached James City Formation. A third possibility is that they are lagoonal to fluvial sands that may or may not be related to the James City Formation.

There is a problem in determining the behavior of sea level during the deposition of the Small sequence. If each organic horizon represents a separate transgression and regression, then in

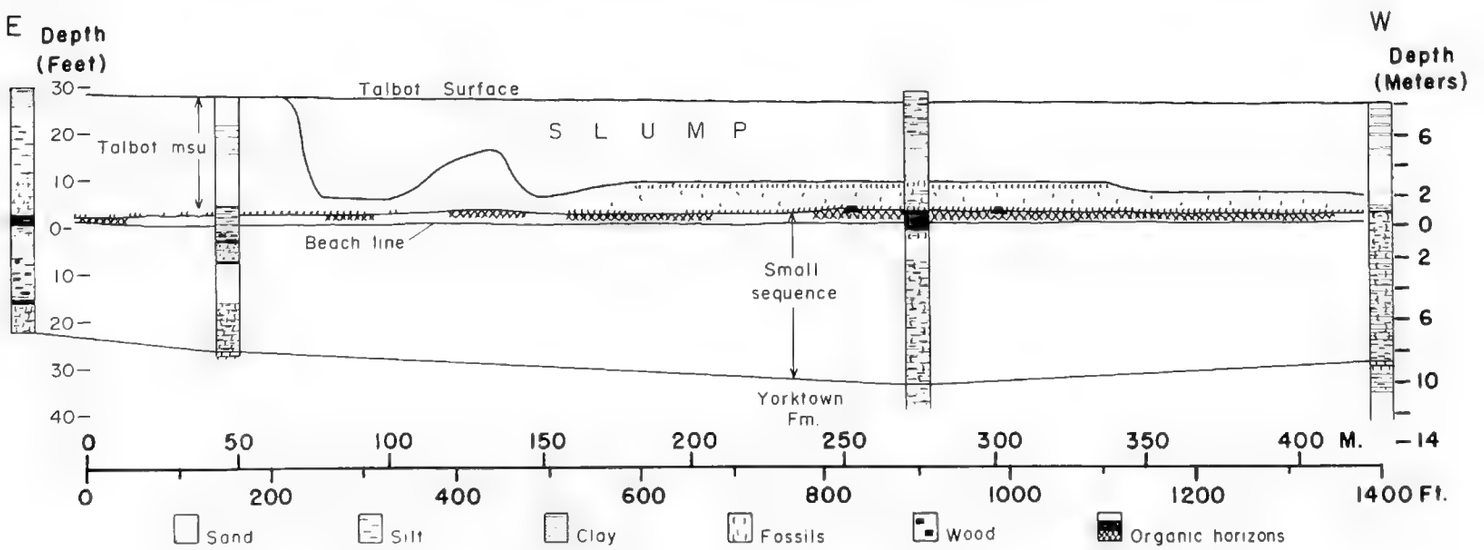


Figure 10.—Sediments exposed at Flanner Beach, North Carolina. This section is a composite of auger holes (shown by the vertical columns) and the exposed section in the bluff on the south bank of the Neuse estuary. The portion of the bank covered by slump is shown. The section below the beach line is known from auger hole information only. (msu = morphostratigraphic unit; Small sequence = Croatan Formation.)

some areas there have been at least five of these. However, it can be suggested also that sea level may have risen in minor increments during deposition of the Small sequence, and sediment accumulation may more or less have kept pace with this rise in the manner known to be taking place in North Carolina lagoons today (Ingram, 1968). The first hypothesis requires repeated rise and fall of sea level with transgression and regression, but the second one requires only that the shoreline remain somewhere within a limited geographic area as sea level rises.

The Small sequence is well exposed in the Lee Creek Mine. The unit exhibits many of the aspects of variability that characterize the Small sequence elsewhere. The most spectacular bed in the mine is a lens of extremely fossiliferous incline-bedded sands on the north face of the pit. Mollusks and colonial corals are very abundant. The steepness of the inclined bedding, about 15°, with large shells as clasts is quite spectacular. It is analogous to the over-wash of a sandbar cited at Yorktown, Virginia, in the Yorktown Formation (G. H. Johnson, 1972:22, 39). The shell unit at Lee Creek Mine grades vertically and laterally into beds of sand with fossils scattered singly or as stringers or into unfossiliferous silty sand. The Small sequence in its upper portion is fine silty sand with some organic stains, so contrasting in appearance to the incline-bedded fossiliferous sand that one might easily place it in the overlying Pamlico msu. However, the layer of scattered pebbles, cobbles, and boulders that marks the base of the Pamlico msu lies above the organically stained Small sequence.

Relation of Small Sequence to Surficial Sediments.—The relations between the Talbot and Pamlico msu and the Small sequence are important in dating and developing a history of the lower Coastal Plain. Locally, such as at the Flanner Beach section, there is a distinct lithologic disconformity separating the Talbot msu and the Small sequence. Yet, if one considers the multiple organic layers of the Small sequence and their relations to one another, there are disconformities within the Small sequence that are just as distinct and may represent as much change in depositional environment. Are we, then, justified in placing a formational break at the base of the *Dinocardium* layer in the Flanner Beach section? We think we are justified because this disconformity has been traced over a wide area, whereas the disconformities within the Small sequence are of very limited geographic extent.

The relation between the Pamlico msu and the underlying Small sequence seems to be much more distinct than between the Talbot msu and the underlying Small sequence. The Pamlico nearly everywhere is sharply separated from the Small sequence by a basal fossil "hash" layer that can be traced for miles, but is not present at the Lee Creek Mine. About 8 out of 10 holes have this hash layer and seldom does it vary more than 3 to 5 feet (0.9 to 1.5 m) in altitude, usually less within a local area.

## Talbot and Pamlico Morphostratigraphic Units

The major morphostratigraphic units (msu) in the area are the Talbot and Pamlico of Stephenson (1912) and other authors. These surface units are lithologically similar to, and difficult to distinguish from, each other.

Talbot Morphostratigraphic unit.—By our definition, the Talbot msu is the surface unit that occurs between the toe of the Walterboro Scarp, altitude 45 feet (13.7 m) and the top of the Suffolk Scarp (Figure 6). The Minnesott ridge sand at the top of the Suffolk Scarp in Beaufort County and Pamlico County is probably associated with the Pamlico msu. We have not mapped the exact areal distribution of the Talbot throughout the Neuse Basin, although its eastern limit, the Suffolk Scarp, has been mapped (Figures 1, 4, 7).

The Talbot msu has almost any texture from sand to silt to clay. It is coarsest at the base and becomes finer toward the top in about half our drill holes. However, as at the Flanner Beach section (Figure 10), there are vertical and horizontal changes in texture over short distances that can range from sands to clays with any one lithology occurring at any level within a vertical section.

Fossils occur near the base of the Talbot only in its eastern part (Figures 5, 8), and then usually in a somewhat clayey matrix. Only 20 of 59 bore holes in the Talbot have marine fossils somewhere within the section, and the largest number of holes with fossils are south of the Neuse River. The fossils may form a very concentrated layer such as the basal *Dinocardium* zone at Flanner Beach (Figures 4, 10), or they may be sparsely scattered throughout a silty or clayey matrix.

The fossils at Flanner Beach (DuBar and Solliday, 1963) and at sections near Bear Creek (Fallaw and Wheeler, 1969; Fallaw, 1973) place the Talbot definitely within the Pleistocene.

Pamlico Morphostratigraphic Unit.—The Pamlico msu includes all surface sediments east of the Suffolk Scarp with the exclusion of Recent eolian sands and swamp or marsh deposits in river valleys and lagoons. The Minnesott Ridge (Figure 7) is a unit that is associated with the Pamlico. It is a ridge of sand 1 mile (1.6 km) or less wide, whose seaward face forms part of the Suffolk Scarp between the Pamlico and Neuse estuaries. The northern terminus of the Minnesott Ridge is about 4 miles (6.4 km) west of the Lee Creek Mine, and the southern terminus is at Minnesott Beach on the Neuse River. The ridge has a maximum altitude of 65 feet (19.8 m). It rises 25 to 30 feet (7.6 to 9.1 m) above the Talbot surface to the west and 50 feet (15.2 m) above the Pamlico surface to the east. The topography of the ridge crest is extremely variable; it may be flat or dune-like with small irregular depressions. Texturally the ridge is sand to loamy sand. We have not found clay or silt lenses in the more than 20 holes we have drilled in it. The ridge sand, along its western edge buries organic layers at the top of the Talbot (Figures 4, 11).

Near the center and eastern part of the ridge, the organic layers and the ridge sands overlie sands and other lithologies of the Talbot msu. The east side of the ridge is the Suffolk Scarp and the ridge sands merge laterally to the east with the clayey and sandy Pamlico which everywhere lies below 20 feet (6.1 m).

The sand texture of the ridge plus the perched

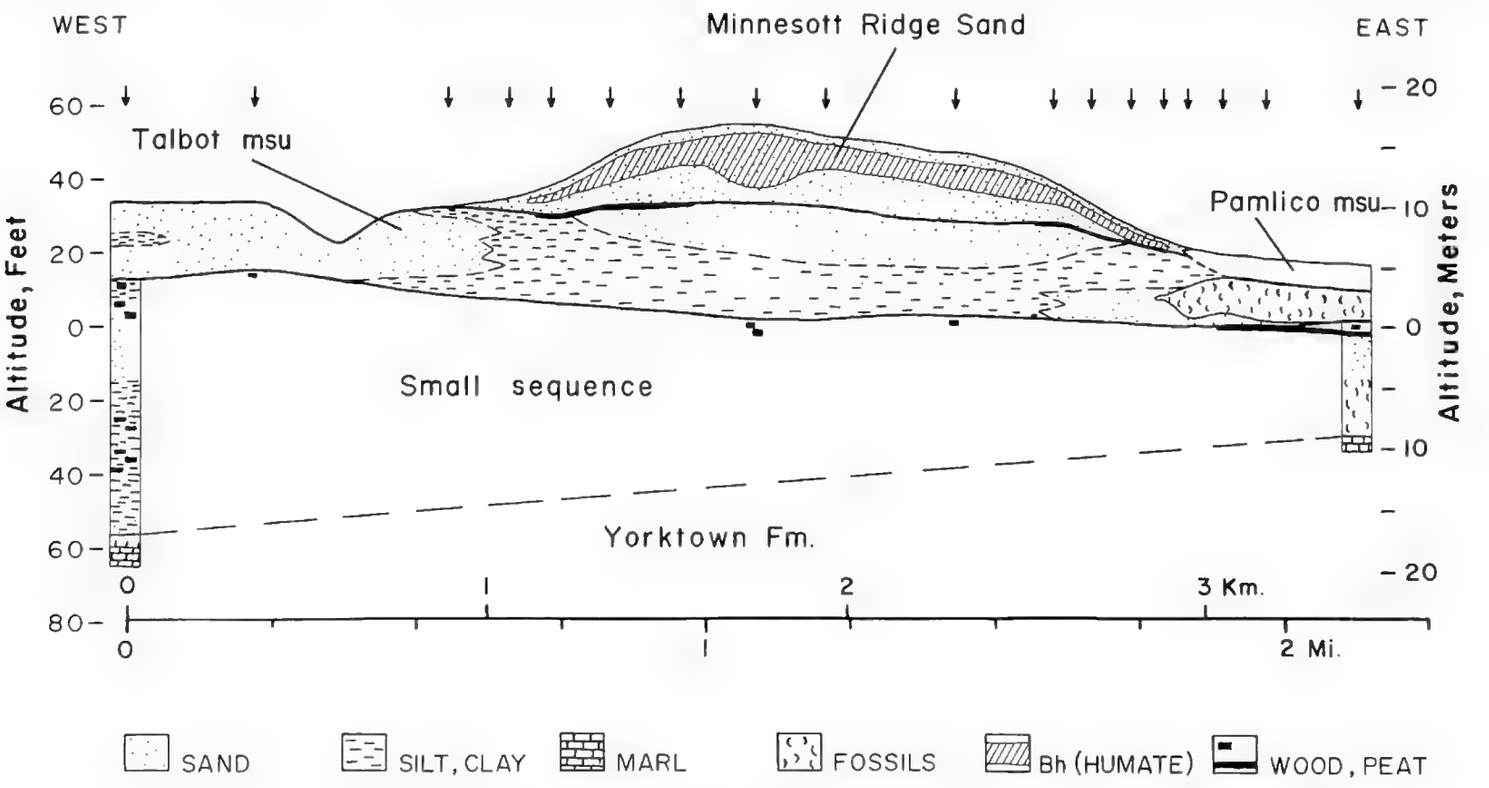


Figure 11.—Cross-section of Minnesott Ridge near Small, North Carolina. (Arrows indicate the auger holes used to construct the cross-section; msu = morphostratigraphic unit; Small sequence = Croatan Formation.)

water levels above the less permeable Talbot have resulted in the accumulation of thick Bh horizons, the humates of geologists (Swanson and Palacas, 1965), in the wetter parts of the ridge. These Bh horizons are the result of organic carbon becoming water soluble and moving downward into the sand from the surface litter (Daniels, Gamble, and Holzhey 1972; Holzhey, Daniels, and Gamble, 1972). These thick, and extremely variable (horizontally and vertically) humates have little or no pollen, no wood (excluding roots), and should not be confused with buried A1 horizons. A section illustrating the morphology of the Bh horizon, the ridge sand, and the contact with the buried organic layer at the top of the Talbot is given below. The location is 0.32 miles (0.51 km) west of the junction of North Carolina Highway 306 and Beaufort County Road 1927 on Road 1927 (Figure 7; locality 3).

| *Depth in feet (meters)* | *Description* |
|---|---|
| 0 to 0.5 (0 to 0.2) | Road fill |
| | MINNESOTT RIDGE SAND |
| 0.5 to 1.5 (0.2 to 0.5) | A1 soil horizon; black (10 YR) fine loamy sand; abrupt to |
| 1.5 to 2 (0.5 to 0.6) | A2 soil horizon; dark gray (19YR 4/1) fine loamy sand to sand; abrupt to |
| 2 to 3.5 (0.6 to 1.1) | Bh1 very dark gray (5YR 3/1) fine loamy sand; organic material covers sand grains; common to many roots, grades downward to |
| 3.5 to 8 (1.1 to 2.4) | Bh2 dark reddish brown (5YR 2/2) fine loamy sand grading downward to very dark grayish brown (10YR 3/2) fine sand; base of Minnesott Ridge sand; abrupt to buried Talbot surface. |
| | TALBOT MORPHOSTRATIGRAPHIC UNIT |
| 8 to 9.5 (2.4 to 2.9) | Dark reddish brown (5YR 2/2) peat; some fine mineral matter intermixed in base; clear to |
| 9.5 to 14 (2.9 to 4.3) | Dark greenish gray (5BG 4/1) very sticky silty clay loam to silty clay; base of hole at 14 feet (4.3 m). |

The Minnesott Ridge is a distinct topographic feature between the Pamlico and Neuse rivers, but there is little evidence of the ridge sand occurring elsewhere along the Suffolk Scarp in North Carolina. The ridge is most certainly associated with the events that resulted in deposition of the Pamlico msu (Figure 11), because the ridge sand merges with the Pamlico msu on the east and buries peat and other soils or evidence of subaerial weathering at the top of the Talbot msu to the west. We suggest the possibility of the area to the east being open ocean.

The Pamlico sediments east of the Minnesott Ridge commonly are fine textured in the upper 3 to 5 feet (0.9 to 1.5 m) and range from sands to silty clay loams from 5 feet (1.5 m) to the base. Marine fossils are abundant both as a basal hash layer and a few to common shells dispersed throughout a sandy matrix. About three-fourths of the 45 bore holes through the Pamlico had marine fossils. The fossils in the Pamlico are equally abundant north and south of the Neuse estuary. The sediments of the Pamlico msu have an altitude range of +20 to −20 feet (+6 to −6 m). Marine fossils may occur in the Pamlico at altitudes of about +5 feet (+1.5 m) to the base. The altitude of the fossils at Flanner Beach (Figure 10) is within the altitude range of the Pamlico msu, but the Flanner Beach section is Talbot msu because it occurs west of the Suffolk Scarp and the strata associated with the fossils rise to nearly +30 feet (+9 m).

The Pamlico sediments are well exposed in the Lee Creek Mine. The sediments range from sands to silt loams and lack conventional fossils. But the sands have a spectacular assemblage of the trace fossils (lebensspuren) that represent the burrows and chambers of various mollusk, arthropod, and anemone infauna (Welch, Frey, and Belt, 1972; Austin, Molnia, and Curran, 1973; Belt, Frey and Welch, herein). One of the beds is a steeply crossbedded fine sand deposited by strong currents as in a tidal channel. On the other hand, one unit has abundant fragments of tree roots in it. At the base of the Pamlico at the Lee Creek Mine scattered pebbles, cobbles, and even boulders lie along the unconformity. One boulder recovered from the face of the pit was 16 inches (40.6 cm) along the long dimension.

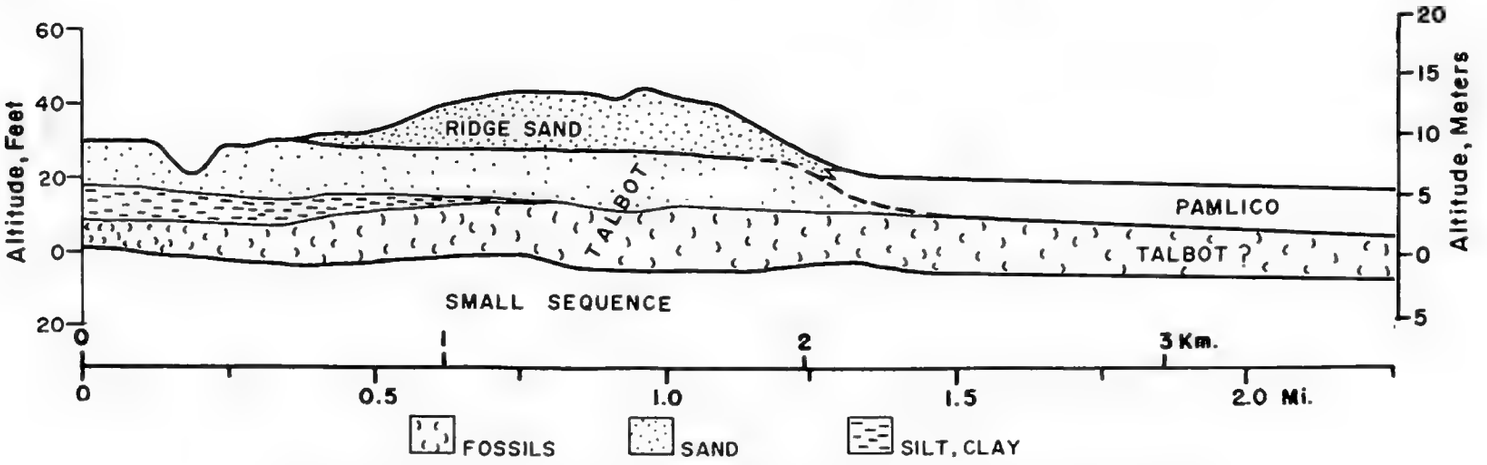


FIGURE 12.—Cross-section of Minnesott Ridge near Arapahoe, North Carolina. (Small sequence = Croatan Formation.)

## Discussion

We now believe that our studies show (1) a persistent unconformity between the Yorktown Formation and Croatan Formation (Small sequence), (2) the presence of both marine and nonmarine aspects of the Croatan Formation, and (3) an unconformity between the Croatan and later Pleistocene units. Typically, an organic-rich nonmarine layer in the Croatan Formation lies just beneath this unconformity. These characteristics of the Croatan Formation may be seen both regionally and in the walls of the Lee Creek Mine.

During the initial work on the Atlantic Coastal Plain, Stephenson (1912) separated the Talbot and Pamlico msu largely on the supposition that a scarp meant a new cycle of transgression and regression. He mapped a different formation between each pair of scarps, although he had little direct evidence of formational changes. The scarps and surfaces that Stephenson mapped in North Carolina generally hold; he did an excellent job in a short time with very poor topographic coverage. Whether or not a new formation starts at the toe of each scarp, however, may be debated for years because even intensive work with drill rigs and modern laboratory techniques frequently leaves us only the numbers and few facts, but not unequivocal proof.

We have three detailed traverses across the Suffolk Scarp that will allow us to speculate somewhat on the possible stratigraphic changes across it (Figures 4, 8, 11, 12). South of the Neuse estuary, the Suffolk Scarp is a somewhat indistinct feature with a toe altitude between +15 and +20 feet (+4.6 and +6.1 m). Several drill holes across the scarp suggest that the Pamlico to the east is inset into and slightly below the Talbot that lies to the west (Figure 8). This relation is based upon a fossil hash assumed to be at the base of the Pamlico that occurs at a reasonably uniform level over wide areas east of the scarp. The traverse across the Suffolk Scarp in Beaufort County can be interpreted in at least two ways. We presently argue that the Minnesott Ridge sands grade into the silty and clayey upper part of the Pamlico at the toe of the scarp. The fossiliferous bed near the base of the Talbot west of the scarp is truncated by the overlying Pamlico farther east. The change in lithology across this contact between the Pamlico and Talbot east of the scarp may be minor.

A second possibility is that the Pamlico and Talbot are one sedimentary unit. This would make the Minnesott Ridge a post-depositional feature probably associated with a high stand of sea level at about +20 feet (+6 m), and it would make the Pamlico surface an erosion surface. This was the view of Fallaw and Wheeler (1969) who regarded the Neuse Formation (the type section of which is in the Talbot msu on the North bank of the Neuse estuary) as continuous across the scarp.

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# Observations on the Paleoecology and Formation of the "Upper Shell" Unit, Lee Creek Mine

*H. Allen Curran and Patricia L. Parker*

ABSTRACT

The "Upper Shell" unit at the Lee Creek Mine (Pliocene age, maximum thickness 3 m) is remarkable for its concentration of well-preserved mollusk shells in a sparse quartz sand matrix, and it is dominated by several species of bivalves, with many shells articulated. The unit can be subdivided into three bivalve assemblage zones characterized by associations of dominant species. Zone 1 is dominated by *Mercenaria mercenaria*, an infaunal, shallow- to medium-burrowing, siphonate clam. Zone 2 is characterized by an epifaunal bivalve assemblage that includes *Glycymeris americana, Argopecten eboreus*, *Anomia simplex*, and *Ostrea meridionalis*. Thin but highly concentrated accumulations of *Argopecten* and *Anomia* form distinct layers within zone 2. Zone 3 is marked by a return of *Mercenaria mercenaria* accompanied by specimens of *Geukensia* sp. and an increase in oyster shells. The characteristics of the zones of the "Upper Shell" unit strongly suggest that these shell beds were formed by a series of localized catastrophic events that produced mass mortality of the molluscan assemblages, rather than by processes of gradual shell accumulation. The disappearance of *Mercenaria mercenaria* from the sequence may have been due largely to the inability of juveniles of this species to penetrate a shell pavement formed immediately after a mass mortality event. Return of *Mercenaria mercenaria* in zone 3 marks a change in bottom environmental conditions in the area. The overlying "Shell Hash" unit contains the bivalve *Corbicula densata,* representative of lower salinity conditions. This unit consists primarily of shell material reworked from the underlying "Upper Shell" unit and probably represents an accumulation formed in an estuarine tidal channel.

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## Introduction

One of the most prominent units revealed by strip mining operations at the Lee Creek Mine of Texasgulf Inc. is a shell bed with a maximum thickness of 3 meters located toward the top of the exposed stratigraphic sequence. Known locally as the "Upper Shell" unit, these beds are remarkable for their abundant, well-preserved megafossils, consisting largely of bivalves, gastropods, and large coral heads. Many of the mollusk shells are whole and unworn, bivalves are frequently articulated, and some of the shells retain faint coloration patterns.

During the summers of 1971 and 1972, the actively worked and advancing western face of the mine (approximately 1100 m in length) was cut by a series of five equidistantly spaced, parallel drainage trenches of up to 240 meters in length, which ran normal to the mine's west wall (Figure 1). Each of these trenches cut to the base or slightly below the base of the "Upper Shell" unit and provided continuous and easily accessible exposures. At first glance the "Upper Shell" unit appeared to be a homogenous sequence, conspicuously dominated by large, flat-lying bivalve shells. Closer inspection revealed that the unit consisted of a sequence of three major shell

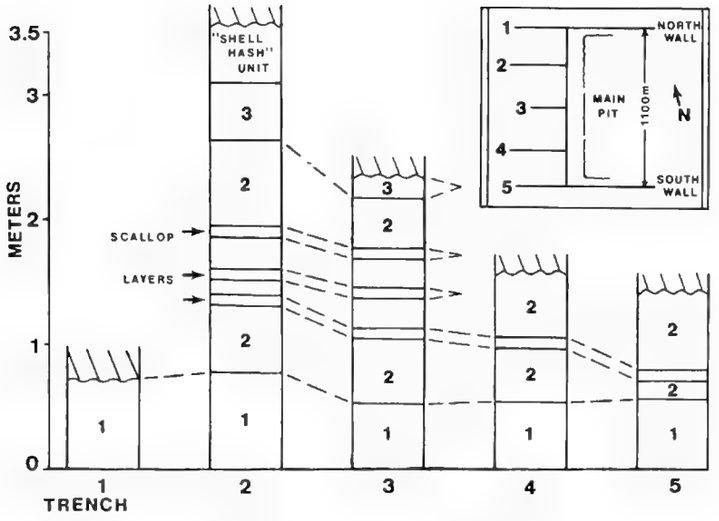


FIGURE 1.—Correlation of bivalve assemblage zones 1–3 of the "Upper Shell" unit between sections established in the five drainage trenches that ran normal to the west wall of the Lee Creek Mine in 1971–1972. Arrows mark positions of layers with concentrations of *Argopecten* and *Anomia* shells that cut zone 2. The "Shell Hash" unit also is exposed prominently on the south wall of the mine. Inset diagram shows the spatial distribution of the drainage trenches in 1971.

layers, each characterized by a distinctive assemblage of bivalve species.

The varied nature and good exposures of the "Upper Shell" unit presented an excellent opportunity for detailed sampling of the shell layers. Paleoecological data derived from the samples include the relative abundances of dominant species in each layer, changes in species abundances through the section, and size-frequency analyses of selected species. These data have enabled a paleoecological interpretation of the varying bivalve associations. The question of how extensive shell layers like this one are formed is intriguing, and our work has enabled us to speculate concerning mechanisms of origin of these shell beds.

The full extent of the "Upper Shell" unit was examined in each of the drainage trenches and the thickness of each faunal zone measured and recorded. Bulk samples were taken from each shell layer and all trenches in the 1971 trench positions (Figure 1). The trench network permitted close correlation of faunal zones between the five trenches. Samples of 1 cubic foot (0.028 $m^3$) volume (dimensions 1×1×1 ft where possible) were dug from the trench faces and placed in a large wooden wash box similar to that described by McKenna (1965). Samples were then field washed in the drainage stream at the base of each trench and boxed for laboratory study. One sample was taken from each layer thinner than 0.3 meter and two samples from layers thicker than 0.3 meter.

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## The Stratigraphic Setting

The "Upper Shell" unit consists dominantly of flat-lying, well-preserved bivalve shells in a poorly consolidated matrix of light gray, fine to coarse quartz sand and fragmented shell. At most points of exposure the shells and shell fragments are tightly packed with little surrounding matrix (Figure 2A, B), although the amount of fine sand, silt, and clay increases greatly at some places. Designated by Gibson (1967:639, fig. 4) as unit 8 of the Yorktown Formation, the "Upper Shell" unit directly overlies a partly indurated, medium to coarse, carbonate cemented quartz sandstone known locally as the "Boulder Bed" (unit 7 of Gibson). The detailed stratigraphy of the entire section above the "Boulder Bed" of the Yorktown Formation, including all units recognized in this study, is presented in Figures 3 and 4 of Belt, Frey, and Welch (this volume).

Questions concerning the age and formational assignment of the "Upper Shell" unit have not been entirely resolved. Although the shell bed previously has been assigned to the Yorktown Formation (Gibson, 1967), the contact between the "Upper Shell" unit and the underlying "Boulder" bed is easily recognized and may represent a significant break in the local stratigraphic sequence. Hazel (p. 84, herein) refers Gibson's units 6–9 of the Yorktown Formation to the Croatan Formation and considers these beds to be late Pliocene-early Pleistocene in age. The "Upper Shell" unit has been traced regionally to the south through samples from auger drillings reported on by Wheeler, Daniels, and Gamble (this volume). They use the name James City Formation (or Croatan Formation) for these shell deposits and consider them to be of Pliocene age. This correlation is supported by DuBar, Solliday and Howard (1974:109).

## Description of the Shell Bed

At the time of this study (1971–1972), weathering and ground water percolation had caused considerable slumping and iron oxide discoloration of the trench walls. On fresh surfaces, the bivalve shells formed distinct horizontal layers dominated by one or two species. We were able to recognize three distinct bivalve faunal assemblages in the "Upper Shell" unit in the area of the trenches. The faunal zones were dominated by abundant, largely mutually exclusive occurrences of three species: *Mercenaria mercenaria* (Linnaeus), *Glycymeris americana* (DeFrance), and the scallop *Argopecten eboreus* (Conrad). We measured a maximum thickness of 3 meters for the "Upper Shell" unit at the 1971 location of trench 2 (Figure 1). At this location and in trench 3, three faunal assemblage zones could be recognized and established. Zone 2 is cut by several thin (0.15 m) layers dominated by *Argopecten eboreus*. Trenches 1, 4, and 5 had incomplete and thinner sections of the "Upper Shell" unit, but one or more zones of the unit were present in each of these trenches. Characteristics of the faunal zones are illustrated in Figure 2. The dominant faunal constituents and maximum thickness of each zone are as follows: ZONE 1 (maximum thickness 0.6 m): *Mercenaria mercenaria* (Linnaeus) dominant. ZONE 2 (maximum thickness 2.15 m): *Glycymeris americana* (DeFrance) dominant, zone cut by thin layers (0.15 m) composed primarily of shells of *Argopecten eboreus* (Conrad) and *Anomia simplex* d'Orbigny. ZONE 3 (maximum thickness 0.25 m): *Mercenaria mercenaria* (Linnaeus), dominant; *Ostrea meridionalis* Heilprin and *Geukensia* sp., common.

The horizontal bedding pattern of the "Upper Shell" unit is broken by steeply dipping (up to 30°), shell-dominated cross-beds along much of the north wall of the mine. Shells in these beds are disarticulated and often broken. The large valves and valve fragments that make up the bulk of these beds typically exhibit worn surfaces resulting from transport under high energy conditions. The anomalous bedding pattern and worn condition of shells forming these cross-beds indicates that these beds were deposited after formation of the "Upper Shell" unit. As one moves laterally away from the cross-beds into the area of trench 1 (west), beds of zone 1, characterized by flat-lying, often articulated *Mercenaria mercenaria*, become visible.

We interpret these cross-beds as representative of a localized event of reworking and redeposition of shells derived primarily from the "Upper Shell" unit. This reworking event possibly occurred during the formation and filling of a tidal channel as part of the general reworking of shells associated with the formation of the overlying "Shell Hash" unit. A common component of the cross-bedded shell accumulation is large valves of the oyster *Crassostrea virginica* (Gmelin). This species does not occur in the beds of the "Upper Shell" unit, but the species may have flourished in the vicinity of or along the banks of the now-filled tidal channel, thus explaining its occurrence with the reworked shells. Modern analogs supporting this interpretation have been reported by Howard and Frey (1973:1177, fig. 8) and Wiedemann (1972) from estuaries of the Georgia coast. Here Holocene shells and shells reworked

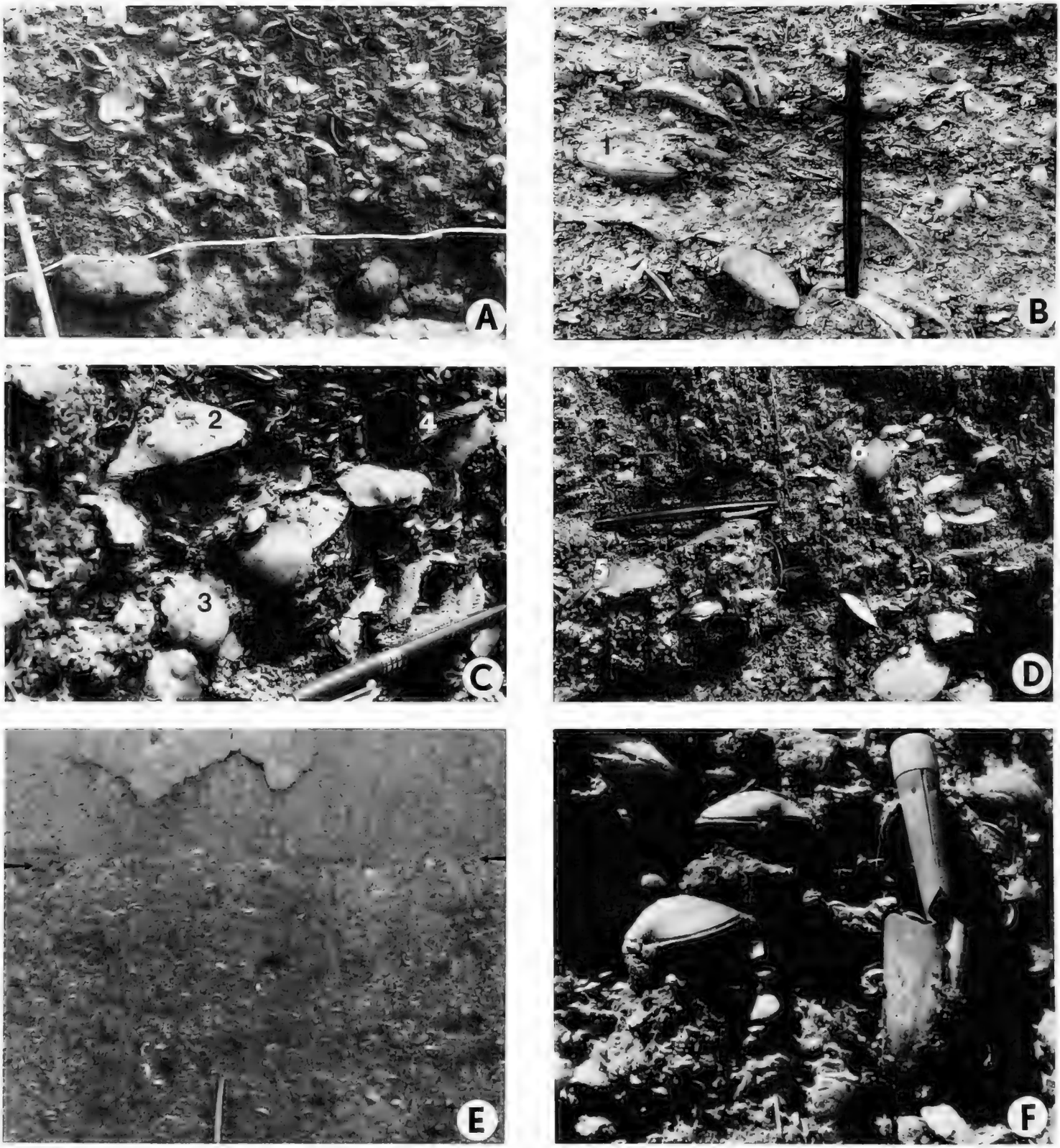


FIGURE 2.—A, Contact between the "Boulder Bed" and *Mercenaria* dominated zone 1 of the "Upper Shell" unit. B, Close-up of zone 1 showing large *Mercenaria* valves (1) which form a hard shell pavement at top of the zone. C, Concentration of epifaunal bivalves, *Glycymeris* (2), *Anomia* (3), and *Argopecten* (4) characterize zone 2. D, Thin layers of concentrated valves of *Argopecten* (5) and *Anomia* (6) form a subassemblage within zone 2. E, South wall of mine showing sharp contact (arrows) between "Upper Shell" unit and overlying "Shell Hash" unit. F, Close-up of zone 2 showing articulated *Glycymeris* specimens.

from pre-Holocene deposits occur in tidal channel accumulations, with valves of *C. virginica* frequently dominating the accumulation.

Overlying the "Upper Shell" unit is a shell hash bed of variable thickness (maximum thickness 0.4 m in trench 2; 1.2 m along south wall of mine, see Figure 2E). This zone is referred to as the "Shell Hash" unit by Belt, Frey, and Welch (this volume). It consists of poorly sorted, fine to coarse quartz sand with variable amounts of silt and clay, woody debris, and abundant shell fragments, including whole, articulated valves of the clam *Corbicula densata* (Conrad). As will be discussed subsequently, the presence of *C. densata* indicates a significant change in paleodepositional conditions to an estuarine environment of lowered salinity. We interpret the "Shell Hash" unit to represent an episode of shell reworking with the major part of the fragmented shell derived from the underlying "Upper Shell" unit. As Howard and Frey (1973:1177) have pointed out, stratigraphic mixing of this type probably has occurred repeatedly in the Cenozoic history of the Atlantic Coastal Plain. Belt, Frey, and Welch relate the "Shell Hash" unit to the depositional cycle that includes their overlying "Mud and Sand" unit. At many locations in the pit, we found that the upper part of the shell hash increased markedly in silt and clay content and formed a gradational contact with the overlying "Mud and Sand" unit, whereas at other points, the "Shell Hash" unit is cut by channels now filled with mud and sand. It is, therefore, difficult to establish precise timing for the reworking event, but the evidence for reworking as represented by the "Shell Hash" unit is strong.

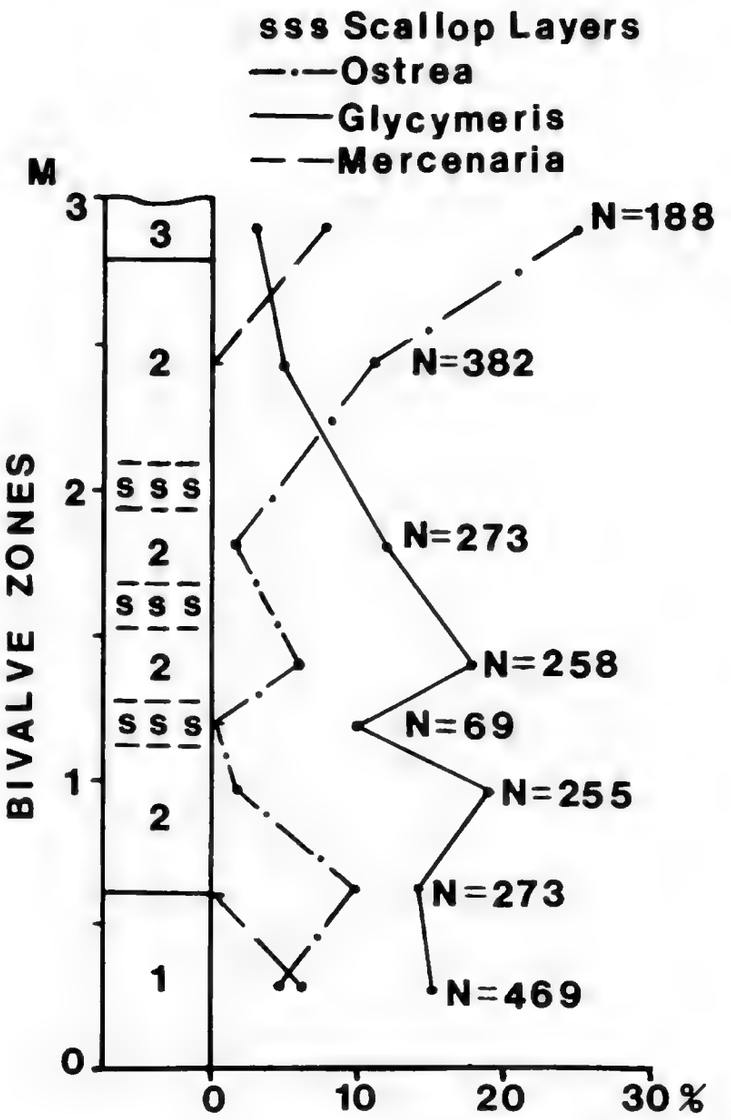


FIGURE 3.—Plot of the relative abundances of *Glycymeris americana*, *Mercenaria mercenaria*, and *Ostrea meridionalis* based on the number of specimens of each species in bulk samples from trench 3. (N = total number of identifiable bivalve specimens in each sample.)

## Paleoecology and Paleodepositional Environments

Based on its foraminiferal assemblage, Gibson (1967:646) postulated that the "Upper Shell" unit was deposited in warm-temperate subtidal waters of 15 meters or less. Blackwelder and Ward (in prep.) have completed a detailed taxonomic study of the molluscan fauna of the "Upper Shell" unit and adjacent beds, and they suggest that these beds, including the overlying "Shell Hash" unit, originated during the development of an offshore bar system. We agree that shallow subtidal conditions existed during the time of formation of the "Upper Shell" unit, but we propose that the overlying "Shell Hash" unit represents an accumulation of primarily reworked shells that formed in an estuarine tidal channel. The pronounced transition that occurs in the composition of the molluscan assemblages of the "Upper Shell" unit (Figure 3) indicates that sig-

nificant changes occurred in the molluscan bottom communities during formation of this shell bed.

The molluscan assemblage zones can be grouped into several different types based on the life mode of the dominant bivalve species. The first of these assemblages, represented by zone 1, consists dominantly of infaunal suspension feeders characterized by a population of large *Mercenaria mercenaria* (Figure 2A, B). These shallow- to moderately deep-burrowing, siphonate clams were sediment-surface suspension feeders. Large numbers of specimens of the shallow-infaunal, nonsiphonate suspension feeders *Astarte concentrica* Conrad and *Venericardia granulata* Say also were present. Other shallow-infaunal suspension feeders include species of the bivalve genera *Abra*, *Anadara*, *Corbula*, *Diplodonta*, *Macrocallista*, *Noetia*, and *Spisula*, all of which occurred in small numbers. Numerous juveniles of *Glycymeris americana*, small oysters, and a few scallops were the major epifaunal suspension feeding bivalves. Carnivorous and herbivorous gastropods in low numbers also formed part of the epifauna.

Zone 2 represents a second bivalve assemblage dominated by abundant epifaunal/semi-infaunal suspension feeders, particularly *Glycymeris americana* (Figure 2C, F). Most species of *Glycymeris* have had or have a life mode similar to that of the modern species *G. pectinata* (Gmelin). Stanley (1970:127–128) found that in the Florida Keys living individuals of *G. pectinata* commonly lie free on coarse bottom sediments or buried under a thin layer of sediment with posterior current openings and sometimes the shell margin itself exposed. Indeed, Thomas (1975) has postulated that glycymerids, with their evolutionarily conservative and functionally generalist traits, have occupied coarse bottom and current-swept shallow marine environments throughout their history. Thomas' studies (summarized 1975:223–225) of the occurrence of *G. americana* in Neogene beds of the Atlantic Coastal Plain show that *G. americana* favored an unstable shell gravel-sandy substrate. Although *G. americana* may have been covered by a thin layer of sediment, it lived essentially unprotected from strong current or wave action sufficient to cause burial and mass mortality. Other epifaunal suspension feeders present in zone 2 include numerous specimens of *Ostrea meridionalis* which are larger (10–14 cm) than those of zone 1, and concentrations of large numbers of *Anomia simplex* d'Orbigny, *Argopecten eboreus*, and the gastropod *Crepidula aculeata* (Gmelin). *Mercenaria mercenaria* is completely absent from this zone, although specimens of the shallow-infaunal, nonsiphonate bivalves *Astarte concentrica* and *Venericardia granulata* remained common.

Within zone 2 are thin but persistent shell layers of a bivalve subassemblage, composed almost exclusively of flat-lying, frequently articulated valves of the scallop *Argopecten eboreus* and single valves of *Anomia simplex* (Figures 2D, 4), both epifaunal suspension feeders. The origin of these layers will be discussed in the following section.

An intriguing paleoecological question presented by this sequence within the "Upper Shell"

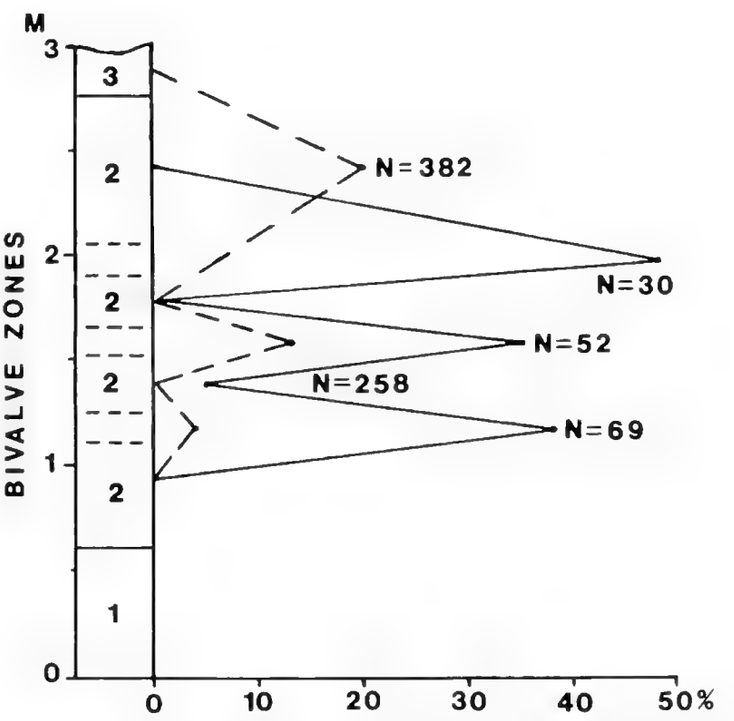


FIGURE 4.—Plot of the relative abundances of *Argopecten eboreus* and *Anomia simplex* indicating the concentrations of these epifaunal bivalves in thin layers within zone 2. (N = total number of identifiable bivalve specimens in each sample; dashed line = *Anomia*; solid line = *Argopecten*.)

unit is, "What caused the disappearance of the *Mercenaria mercenaria*–dominated infaunal assemblage and its replacement by the *Glycymeris americana*–dominated epifaunal assemblage?" The large number of articulated valves and the essentially unworn condition of the fossils strongly suggest that these clams were killed by a catastrophic event resulting in local mass mortality[1] without subsequent transport of the shells. Mass mortality of shallow-infaunal clams like *M. mercenaria* would likely result in the formation of a shell pavement on the substrate surface. As suggested by Gernant (1970:54), the formation of a shell pavement (Figure 2B) would make it difficult or impossible for shallow- to medium-depth burrowers, such as *M. mercenaria*, to resettle until a soft bottom substrate of sufficient depth is reformed. Thus a likely explanation for the disappearance of *M. mercenaria* above zone 1 would be that, following the formation of a shell pavement, juveniles of *M. mercenaria* were prevented from recolonizing because they could not penetrate the shell pavement. This would open the way for *G. americana*, an essentially epifaunal clam capable of colonizing the newly formed shell pavement, to establish itself and become the dominant bivalve of the overlying zone.

Juvenile specimens of some infaunal bivalves which reach large adult sizes, such as *Eucrassatella*, *Macrocallista*, and *Barbatia*, do occur with *Glycymeris americana* in small numbers. If lack of sufficient depth of sediment were the only deterrent to *Mercenaria mercenaria* survival, it would seem likely that some juveniles of *M. mercenaria* would be present. The disappearance of *M. mercenaria* may represent only local displacement of this clam to a nearby geographic area that presented more favorable bottom conditions for burrowing. On the other hand, this disappearance might also be related to more fundamental environmental changes, such as increased water depth and/or salinity that proved detrimental to *M. mercenaria*. The transition from zone 1 to zone 2 in the "Upper Shell" unit can be recognized clearly in the area of the Lee Creek Mine, but further work on the regional characteristics of the "Upper Shell" unit will be necessary before the true magnitude of this transition can be gauged.

In zone 3, *Mercenaria mercenaria* reappears (Figure 3), and this reappearance is coupled with a sharp decline in the population of *Glycymeris americana*. Specimens of the shallow-infaunal, suspension-feeding bivalve *Eucrassatella* sp. also increase in number, and specimens of the mussel *Geukensia* sp. and *Ostrea meridionalis* are abundant and possibly indicate a change to conditions of lowered salinity. This assemblage represents the final stage in the development of the "Upper Shell" unit.

The overlying "Shell Hash" unit contains abundant specimens of *Corbicula densata*, some of which are articulated. *Corbicula* has wide distribution in fresh- to brackish-water deposits of Cenozoic age (Gibson, 1967:646). The presence of this bivalve, the absence of planktonic Foraminifera, and the increased influx of fine-grained sediment formed the basis for Gibson's conclusion that this unit (top of Gibson's unit 8) was formed in a bay or sound of lowered salinity, less than 15 meters deep. We think that the "Shell Hash" unit represents a reworked deposit with the bulk of the shell derived from the underlying "Upper Shell" unit. If this reworking occurred in an estuarine tidal channel, as suggested earlier, the presence of species favoring lowered salinity conditions, such as *C. densata*, mixed with fully marine species would be expected.

### Formation of the Shell Bed

A combination of several factors indicates to us that the zones of the "Upper Shell" unit were

[1] Kranz (1974:237) has used the term "anastrophe" to refer to catastrophes of limited scope and area that generally produce mass mortality in the affected area. Kranz attributed this definition of "anastrophe" to Brongersma-Sanders (1957). However, Brongersma-Sanders (1957:941) did not consider "anastrophe" to be the proper word to use in referring to localized catastrophes affecting marine organisms, although she noted that the word had been used previously in this sense. In this paper, we consider localized catastrophic events and catastrophic burial events to be "anastrophes" and "anastrophic burial" events as defined by Kranz, but we follow the recommendation of Brongersma-Sanders that the word "anastrophe" not be used.

formed by localized catastrophic events that produced mass mortality. These following factors are included. (1) The excellent preservational condition of the fossils, being largely unworn and some with traces of original coloration. Many bivalve and gastropod shells are complete, with the bivalves frequently articulated. The presence of delicate, thin-shelled clams such as *Anomia simplex* and articulated *Argopecten eboreus*, and echinoid plates, which are especially vulnerable to mechanical destruction, indicates little or no transportation and/or exposure to wave action following death. (2) A broad range of size classes is present for the abundant species in our collections. Figure 5 is a size-frequency plot for *Glycymeris americana* that is typical of those plotted for this species and several other abundant bivalves (*Astarte concentrica*, *Venericardia granulata*). The presence of many specimens of different sizes suggests that size-selective winnowing processes were not operative following death of the clams. (3) The majority of shells are generally free of encrusting organisms, such as bryozoans, barnacles, and worm tubes, and do not show the strong effects of marine borers, which normally attack molluscan shells exposed on the substrate following death of the animal.

Mass mortality of marine invertebrates may result from a variety of causes, including vulcanism, rapid temperature and/or salinity changes, toxic water conditions, and the action of severe storms (Brongersma-Sanders, 1957). As indicated by Brongersma-Sanders (1957:942), catastrophes capable of killing benthic organisms may occur repeatedly in a given area. In the fossil record the result of repeated kills would be a sequence of fossiliferous strata, probably much like the sequence of beds of the "Upper Shell" unit.

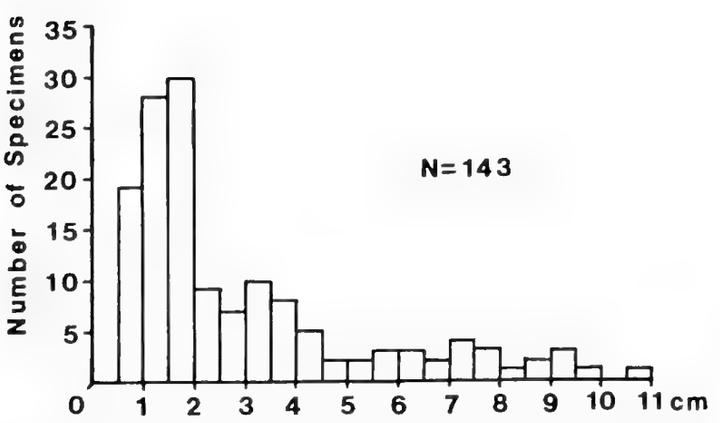


FIGURE 5.—Size-frequency distribution of specimens of *Glycymeris americana* from zone 2 of trench 2. Size measurement is of valve height; right and left valves are included with only one measurement from articulated specimens.

Recently Kranz (1974) has shown that rapid burial ("anastrophic burial") can be lethal to marine bivalves, leading Kranz to conclude that catastrophic burial events probably have been much more important in the formation of ancient shell deposits than previously realized. Severe winter storms and hurricanes occur frequently off the North Carolina coast today, and undoubtedly they also occurred during the time of formation of the "Upper Shell" unit. Such storms can be highly disruptive to shallow-bottom environments and are known to be causes of mass mortality (Brongersma-Sanders, 1957). The "Upper Shell" unit, characterized by its abundance of shell material with a minimal amount of sediment matrix, seems indicative of conditions of formation other than by gradual accumulation of shells in a quiet, subtidal environment.

Gernant (1970) described zones of well-preserved, highly concentrated fossils from the Choptank Formation (Miocene) of Maryland. He developed an explanation for these shell concentrations based on a swell-traction mechanism first suggested by Powers and Kinsman (1953) to explain the formation of concentrated shell layers found off the mouth of Chesapeake Bay today at depths of 15 to 45 meters. Powers and Kinsman postulated that large swells produced by offshore storms establish a pressure gradient capable of disrupting the substrate to the extent that epifaunal and shallow- to medium-depth infaunal bivalves would be exposed, relocated on their sides, and smothered by rapid sedimentation following passage of the storm. Experiments by Kranz (1974:260–261) on living bivalves indicate that epifaunal suspension feeders (such as, *Glycymeris* and *Argopecten*) and bivalves that cement to the substrate (such as *Ostrea* and *Anomia*) are particularly vulnerable to rapid burial and are generally unable to escape more than 1 cm of

burial. Shallow-burrowing, siphonate suspension feeders (such as *Mercenaria*) are more adept at escape, being able to cope with and escape from 10–50 cm of rapidly deposited sediment.

The presence of the abundant flat-lying, often articulated valves of *Mercenaria mercenaria* that characterize zone 1 of the "Upper Shell" unit suggests that these clams were killed by a localized catastrophic event, possibly by relocation and rapid burial similar to the mechanism proposed by Powers and Kinsman (1953). As suggested earlier, the formation of a hard shell pavement probably inhibited the recruitment of juveniles of *Mercenaria* and favored the resultant resettlement of the area by epifaunal assemblages dominated by *Glycymeris* and *Argopecten*.

Bivalves of the epifaunal assemblages of zone 2 would have been highly vulnerable to rapid burial. Brenner and Davies (1973) described layers of whole shells of the pecten-like bivalve *Camptonectes* from the Jurassic of Wyoming and Montana. These layers are similar to the concentrated *Argopecten eboreus* layers within zone 2 (Figure 2D) of the "Upper Shell" unit. Brenner and Davies (1973:1694, fig. 12) suggest that "swell lag" deposits such as these were formed by the Powers-Kinsman mechanism.

Kranz (1974:263) noted that fossil assemblages can be biased by catastrophic burial. Thus, it may be possible to produce different fossil assemblages from a single life assemblage. A reasonable example might be the subassemblages of zone 2 of the "Upper Shell" unit dominated by *Glycymeris americana* and *Argopecten eboreus*. The catastrophic burial process may have resulted in the segregation of the epifaunal assemblage into the subzones dominated by *Glycymeris* and by *Argopecten* and *Anomia* (Figures 3, 4). This alternation of layers within zone 2 could well result from multiple anastrophic burial events capable of segregating the epifaunal bivalves of the "Upper Shell" unit.

Zone 3, as discussed earlier, represents a change in environmental conditions suitable for the return of *Mercenaria mercenaria*. However, the concentration of shells and the presence of many articulated valves of *Mercenaria*, *Guekensia*, and *Ostrea* suggest that localized catastrophic kill events continued to be important in the formation of this zone.

## Conclusions

The "Upper Shell" unit at the Lee Creek Mine can be subdivided into three zones based on distinctive bivalve assemblages. Zone 1 is characterized by an infaunal bivalve assemblage dominated by *Mercenaria mercenaria*. Zone 2 consists of an epifaunal/semi-infaunal assemblage characterized by *Glycymeris americana* and is cut repeatedly by thin, concentrated shell layers of *Argopecten eboreus* and *Anomia simplex*. A reappearance of *M. mercenaria* in the sequence along with the occurrence of *Geukensia* sp. and an increase of shells of the oyster *Ostrea meridionalis* define zone 3. The disappearance of *M. mercenaria* from the sequence probably resulted from the formation of a shell pavement, which prevented successful recolonization of infaunal bivalves and facilitated the establishment of an epifaunal bivalve assemblage. Later, environmental conditions changed sufficiently to permit the return of *M. mercenaria*. The bivalve assemblage zones can be recognized in the exposures of the mine area, but further regional work will be necessary before the full geographic extent of the zones can be established.

The preservation of fossils in excellent condition, the large number of articulated bivalves in a broad range of size classes, and the close packing of shells with generally little matrix suggest that zones of the "Upper Shell" unit were formed by localized catastrophic events causing mass mortality of the benthic communities. This mass mortality may have resulted from localized catastrophic burial events due to the action of severe winter storms or hurricanes, with resultant large swells causing disruption of the substrate and subsequent burial of the bottom dwellers. A mechanism of this type has been described by Gernant (1970). However, the possibility that sudden changes in other environmental conditions were responsible for mass mortality of the benthic fauna cannot be ruled out.

The "Shell Hash" unit is composed primarily of fragmented and worn shell material reworked

from the underlying "Upper Shell" unit. The presence of the bivalve *Corbicula densata*, many specimens of which are articulated, suggests that this unit was deposited under conditions of lowered salinity; possibly in an estuarine tidal channel. Analogous reworked shell accumulations have been reported from the modern Georgia estuarine system (Howard and Frey, 1973). The timing of this episode of reworking cannot be established with certainty; it may represent a regression event following deposition of the "Upper Shell" unit, or it may be associated with the deposition of the overlying Pleistocene units as postulated by Belt, Frey, and Welch (this volume).

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# Pleistocene Coastal Marine and Estuarine Sequences, Lee Creek Mine

*Edward S. Belt, Robert W. Frey, and John S. Welch*

ABSTRACT

Pleistocene and uppermost Tertiary sediments in the Lee Creek Mine exhibit remarkable associations of physical and biogenic sedimentary structures. These, and close modern analogs, permit detailed interpretations of depositional conditions. Environments recognized include: supratidal, intertidal, subtidal estuarine, fluvial channel, freshwater swamp, ebb-tidal sand bar, and shallow nearshore shelf or open estuary deposits.

Four sequences of deposition, the uppermost of Sangamon age, were found. These sequences, separated by unconformities, are related to sea-level change by means of transgressive and regressive sedimentary phases. Analysis of the proportion of the respective phases within cycles suggests that the region underwent only moderate tectonic subsidence during the Pleistocene.

## Introduction

Excellent exposures of a wide variety of Pleistocene and older sediments were created by mining operations in the Texasgulf phosphate mine near Aurora, North Carolina (Figure 1). The upper 50 feet (15 m) of section in the pit were studied by John Welch, Edward Belt, Allen Curran, James Austin, and Robert Frey during the summers of 1971 and 1972, and were rechecked by Curran in 1973. Preliminary results were soon announced (Welch, Frey, and Belt, 1972; Curran and Frey, 1972; Curran, Iannicelli, and Frey, 1973). In the present report, essentially completed in 1974, we emphasize sedimentologic aspects of the various facies studied and define cycles of sedimentation that we believe will be of use to students of the Pleistocene in North Carolina and elsewhere. Originally, we expected this volume to appear prior to publication of ichnologic and paleoecologic aspects of the project, emphasized by Curran and Frey. However, these faunal studies, together with analyses of problematical sedimentary structures, have now been published (Bromley et al., 1975; Curran, 1976; Curran and Frey, 1977), and thus form corroborative evidence for interpretation of the depositional environments described herein.

Unfortunately, the sections upon which this report was based were long ago removed by mining operations, and the mined-out area has been reclaimed; of those outcrops, all that remains are numerous photographs, detailed logs, and a few sand samples, reposited at Amherst College. However, the basic stratigraphic section as established herein was still recognized in the mine in 1978. Reconnaissance of the surrounding region by Belt and Austin in 1972 (Austin, Molnia, and Curran, 1973) failed to reveal comparable facies elsewhere. Perhaps exposures in the Lee Creek Mine were unique remnants of Pleistocene facies not found elsewhere; abrupt lateral facies changes are characteristic of many modern estuarine se-

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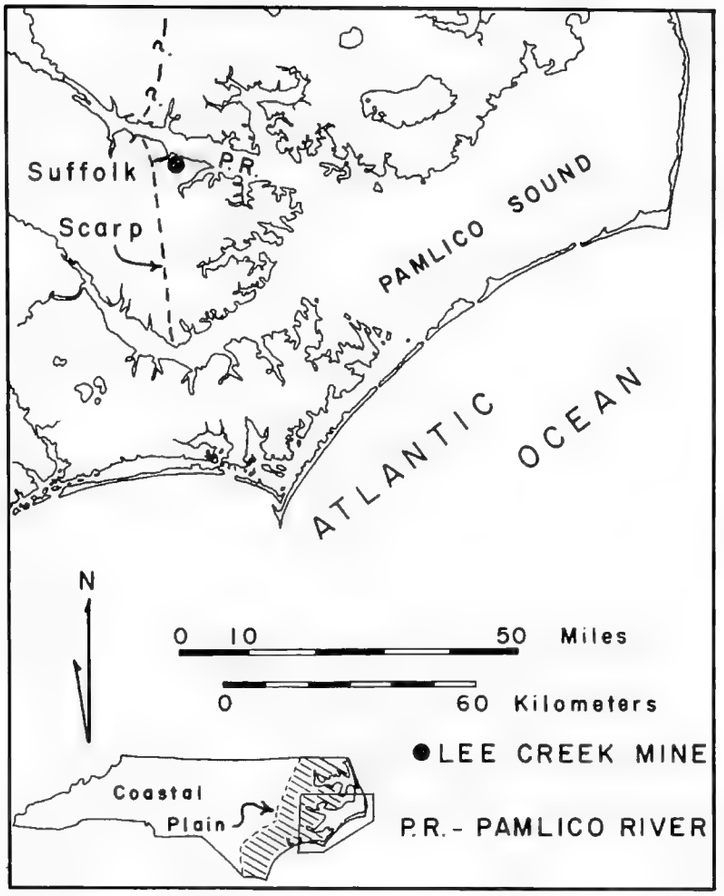


FIGURE 1.—Location of Lee Creek Mine and its relationship to Suffolk Scarp, Coastal Plain of eastern North Carolina.

quences (Howard and Frey, 1980b). On the other hand, perhaps deep leaching of other exposures destroyed much of the evidence. Characteristic sediments in the Lee Creek Mine permitted remarkable preservation of physical and biogenic sedimentary structures, and we found little indication of chemical leaching of heavy minerals (Scott, 1976); the opposite is true of many other Pleistocene deposits of the southeastern Atlantic Coastal Plain.

The section consisted of sand, mud, peaty sand, and coquina facies containing distinctive physical and biogenic sedimentary structures, made all the more notable by their striking similarity to recent analogs. These facies, analyzed with respect to local depositional environments and related to intervening unconformities, suggest four cycles of transgression and regression in the section between the Pliocene Yorktown Formation and Holocene soils. Essentially a three-dimensional correlation was possible within a rectangular area 3600 by 1500 feet (1200 by 500 m) in the mine.

In addition to this report, various other aspects of Pleistocene facies and fossils at the Lee Creek locality are reported in this volume (Whitehead; Wheeler, Daniels, and Gamble; and Curran and Parker), as well as by Blackwelder and Ward (in prep.).

ACKNOWLEDGMENTS.—This project was made possible through financial support from the National Science Foundation COSIP grant GY-7657 to undergraduate students at Williams, Amherst, Mt. Holyoke, and Smith colleges, Massachusetts. Students from Amherst and Smith wrote honors theses on topics related to Lee Creek Pleistocene deposits and fossils. John Welch did an honors thesis on physical stratigraphy and sedimentology of the section described herein, in 1971–1972. Belt was his advisor. Robert Frey was drawn into the research as a result of his visits with Belt and Welch in the field during 1971. Welch's work was followed in 1972–1973 by James Austin's honors thesis. He measured an additional 11 sections in the pit, because the face had by then moved several hundred yards (meters) to the west (Figure 2); his results confirmed those of Welch. We also acknowledge Austin's attempt to correlate the pit succession with sections along the south shore of the Pamlico River west of the mine (Figure 1).

We are especially grateful to Allen Curran for introducing us to the Texasgulf phosphate mine, for making logistical and other arrangements in Morehead City, and for directing the overall field program during the two summers. We also appreciate the cooperation of Texasgulf Inc., in particular June Crawford, Jack Hird, and Jim MacDonald, for allowing us access to the mine and for several pertinent maps showing the position of trenches at the west end of the mine during the two years of study.

H. Allen Curran, Roy L. Ingram, Jack W. Pierce, James D. Howard, Donald R. Whitehead, Jules R. Dubar, and Nicholas K. Coch read various versions of the manuscript and offered valuable suggestions. John E. Sanders suggested several references inadvertently omitted from an

earlier draft. Jeremy Reiskind and Walter H. Wheeler made helpful suggestions in the field. Curran's students, Patricia L. Parker and Sandra K. Iannicelli, supplied useful information on particular stratigraphic horizons. Clayton E. Ray implemented $^{14}C$ dating of our peat samples through the Smithsonian Institution. F.M. Hueber of that institution identified some wood fragments.

## Stratigraphy and Depositional Environments

To our knowledge, no prior sedimentologic study of Pleistocene sediments from the Lee Creek Mine had been made. Previous workers in the general vicinity of the mine concentrated on thin roadside exposures, thicker and rather well-exposed sections along the Neuse and Pamlico River estuaries, or samples from auger holes as deep as 100 feet (30 m). Recent concepts and controversies concerning the Pleistocene of eastern North Carolina were outlined by Richards (1950, 1962, 1969), Fallaw and Wheeler (1969), Daniels et al. (1972), Fallaw (1973, 1975), and DuBar, Solliday, and Howard (1974). The regional correlation and geologic setting for strata reported herein are summarized by Wheeler, Daniels, and Gamble (this volume), to whom the reader is referred for regional perspective. For broader regional relationships, see the summaries by Oaks and DuBar (1974), Blackwelder and Ward (1976), and DuBar and DuBar (1980).

Our field methods consisted of carefully locating the position and elevation of key horizons in sections, logging the strata in detail, noting textures, primary physical and biogenic sedimentary structures, paleocurrent directions, body fossils, and defining lithogenetic units. Grain-size analyses were made on all units (Folk, 1974) in order to define the range of textures present. Detailed logs of measured sections, not reproduced here, may be found in theses by Welch (1972) and Austin (1973). Selected bedding or burrow features were sampled in the field by means of epoxy peels, and numerous photographs were taken in black and white, as well as in color.

General details of the section emerged in 1971 (Welch, Frey, and Belt, 1972) by careful correlation of units throughout the network of trenches at the west end of the mine (Figure 2). A more detailed stratigraphic column (Figure 3) was constructed from these data; subsequent interpretations, and a schematic cross-section (Figure 4) led to our reconstruction of cycles of Pleistocene coastal marine sedimentation (Table 1). Grain-size analyses (Figure 8; cf. Hails and Hoyt, 1969) proved to be much less valuable in facies interpretations than did unit geometry and physical and biogenic sedimentary structures.

Because salinities are such integral parts of our interpretations of depositional environments, we offer the following qualifications of descriptive terms used subsequently: Full marine salinity is 36 ‰; inshore and nearshore-shelf salinities rarely attain that level, however; thus we consider 32 to 36 ‰ as "normal" salinity, 28 to 32 ‰ as "nearly normal" salinity, and 24 to 28 ‰ as "slightly brackish" salinity. Many "normal" estuarine animals can tolerate salinities as low as 10 ‰ for short intervals of time.

The four depositional sequences identified and described here may be characterized briefly as follows:

Cycle I—Upper Shell unit: mostly molluscan shells (many articulated bivalves). Lower Pleistocene or uppermost Tertiary; overlies Pliocene Yorktown Formation.

Cycle II—Two units. (A) Shell Hash unit: coarse quartz sand and broken shells in trough-cross-bedded sets, a "basal conglomeratic sand," overlain by, and in places laterally equivalent to, (B) Mud and Sand unit: sandy member containing flasers, cross-beds, *Ophiomorpha*, and *Skolithos*, and muddy member containing bioturbate textures and *Thalassinoides*.

Cycle III—Current unit: lower member of tabular and trough cross-beds having east-northeast mean trend, containing *Ophiomorpha* and *Skolithos*. Overlain by flaser and wavy bedded mud and sand member containing above trace fossils, *Planolites*, "sitz marks," and several other traces.

Cycle IV—Several units: progression from (A)

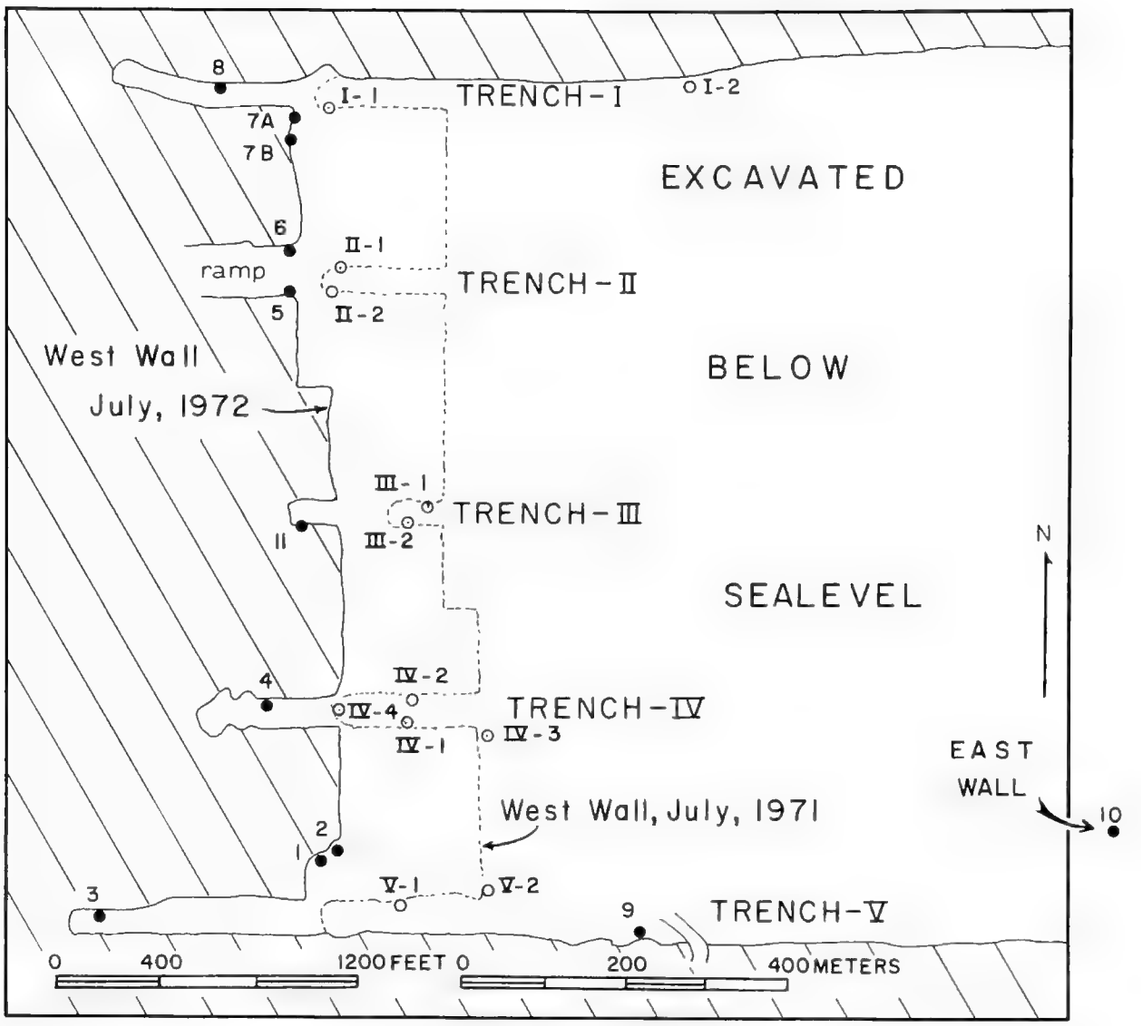


FIGURE 2.—West end of Lee Creek Mine, showing location of sections measured. The 1971 and 1972 positions of trenches are indicated. Open circles represent sections measured by Welch (1972); solid circles represent sections measured by Austin (1973); section 10, east wall, is off the scale of the map.

Channel unit (fluvial channel): trough cross-bedded sand, cut into deposits of cycle III and II, through (B) Peat and Clay unit: clay member having no apparent fossils, into nonmarine peaty member containing a Sangamon temperate flora, ultimately into (C) Mottled unit (marine unit): intensely bioturbated mud and sand containing mollusks.

## Comments on Trace Fossils

Biogenic sedimentary structures were invaluable in our environmental interpretations. Because of this, as well as their possible unfamiliarity to the reader and common misconceptions of trace fossils such as *Ophiomorpha* and *Thalassinoides* (Frey, 1975:33; Frey, Howard, and Pryor, 1978; Frey and Seilacher, 1980), a word about their usefulness and degree of reliability is in order. Primarily, we stress that our interpretations are based not merely upon identification of trace fossil genera, but rather, upon the closeness-of-fit between geometry, configuration, and composition of trace fossils and close analogs known along the present coast of Georgia (Howard and Frey, 1975, 1980a, 1980c; Frey and Howard, 1980) and the Carolinas (Frey, 1970; Allen and Curran, 1974). In most cases, the fit was remarkably close (Curran and Frey, 1977), and we suspect that many of these extant tracemakers are in fact the same species that made the Pleistocene trace fossils.

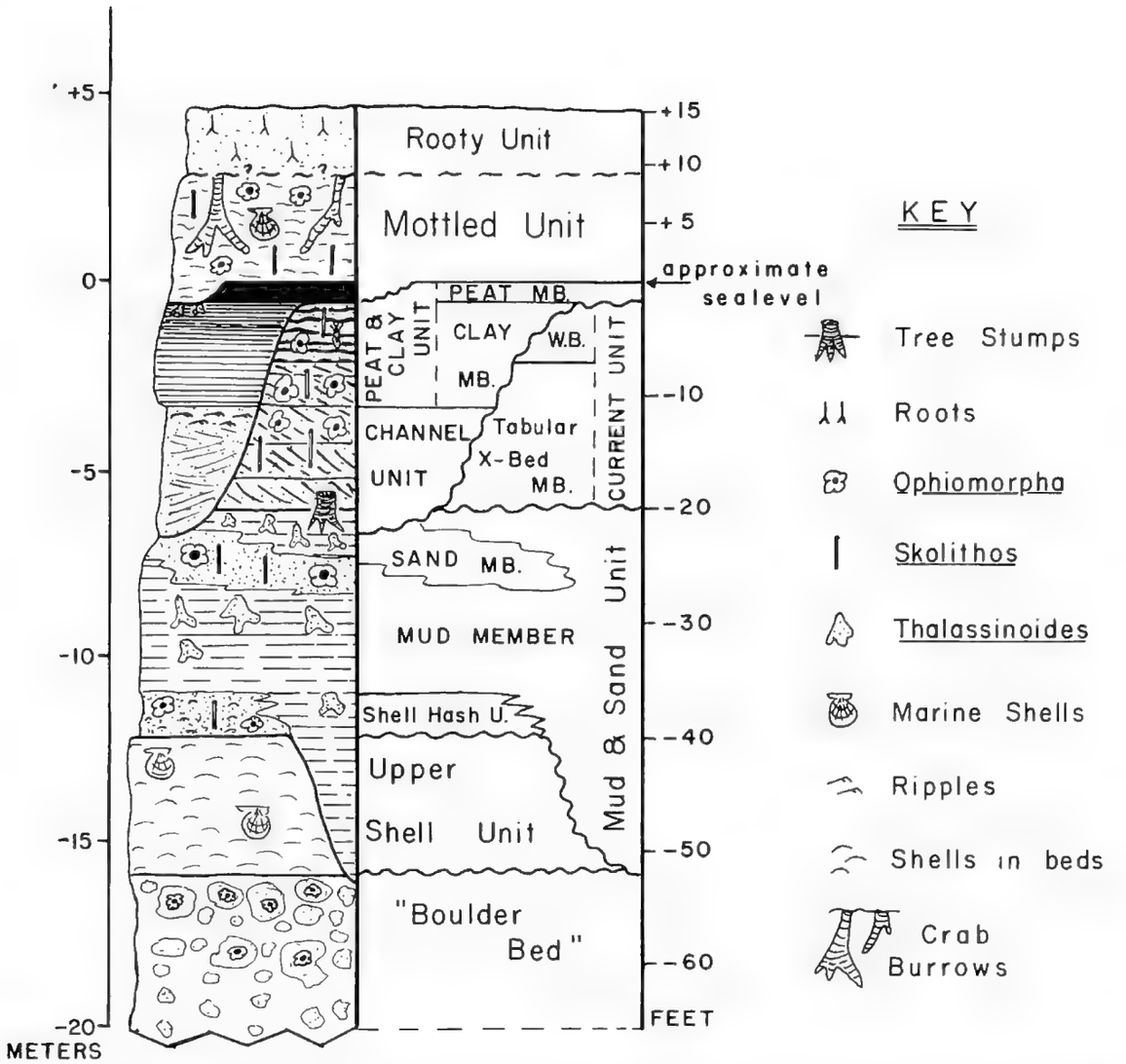


FIGURE 3.—General post-Yorktown stratigraphic column, Lee Creek Mine. Heavy wavy lines represent major unconformities. MB. = member, U. = unit. W.B. = wavy bedded member of Current unit. Diagram emphasizes associations of important burrow types and marine shells.

The ghost shrimp *Callianassa major* is not restricted to beaches or beach-related habitats and is not the only species that constructs *Ophiomorpha*-type burrows (Weimer and Hoyt, 1964); yet most Pleistocene *Ophiomorpha* observed at Lee Creek are virtually identical to modern burrows made by *C. major* on the southeastern U.S. coast (Frey, Howard, and Pryor, 1978). This shrimp inhabits low-intertidal to relatively shallow subtidal sands in waters of normal or near-normal salinity and intermediate to moderately high energy. Such conditions are found along beaches, the nearshore shelf, and in ocean-influenced tidal flats, point bars, and shoals within estuaries and lagoons. *Callianassa biformis* also constructs *Ophiomorpha*-type burrows, but these systems are smaller and more irregularly inclined, and the shrimp tolerates a slightly greater range in salinity, bathymetry, and current velocities. Therefore, it is found in somewhat muddier sediments than is *C. major* (Howard and Frey, 1975, 1980c, fig. 20), and also ranges into deeper and (or) less saline waters.

Similarly, the trace fossil *Thalassinoides* can result from burrowing by various shrimp-like animals and may intergrade with *Ophiomorpha* (Bromley and Frey, 1974; Frey and Seilacher, 1980); but specimens studied by us are remarkably similar to burrows constructed today by the mud shrimp *Upogebia affinis* (Frey and Howard,

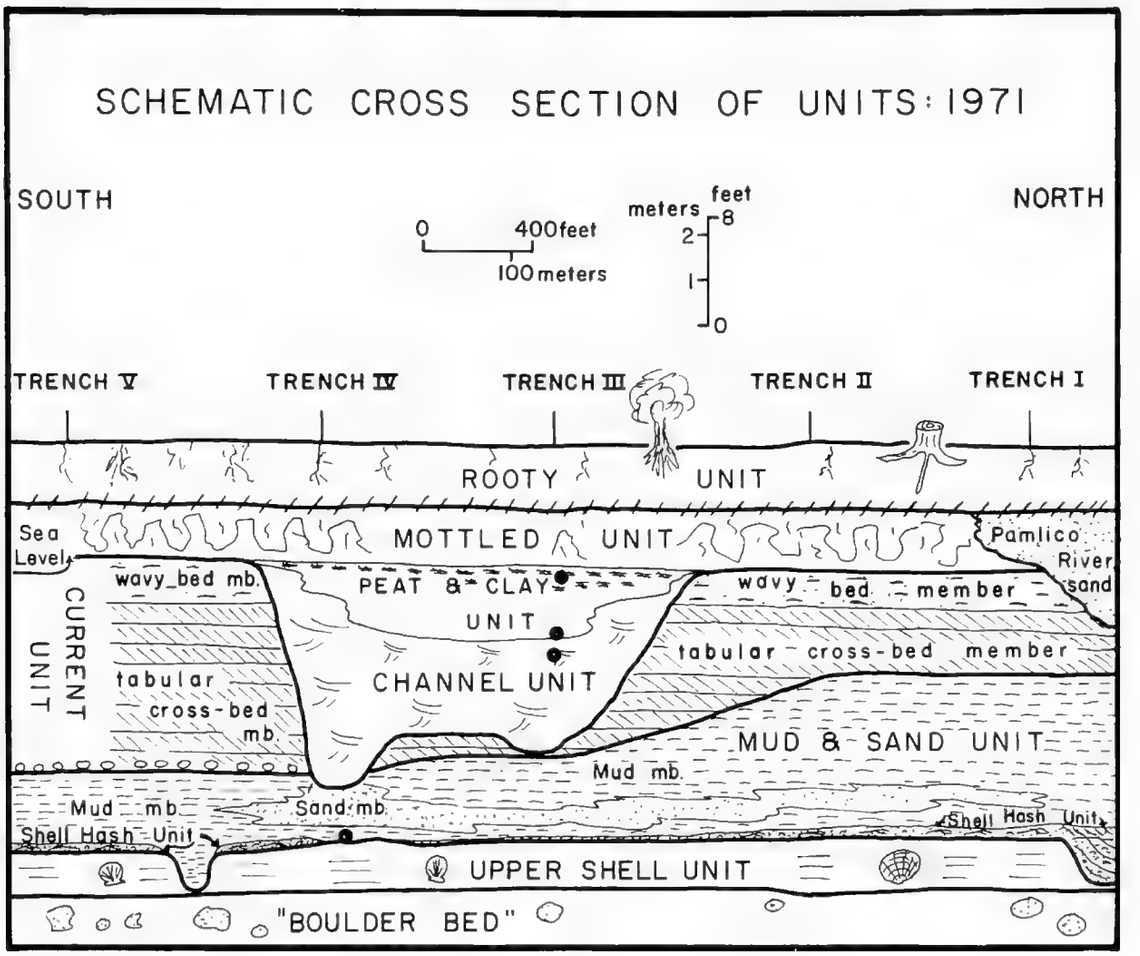


FIGURE 4.—Stratigraphic units. Solid circles represent $^{14}C$ samples (all exceeded 40,000 yr BP). Heavy lines represent unconformities; heavy line with slashes represents possible unconformity. # represents peaty sand. For burrow types, see Figure 3.

1975). On the Georgia coast, *U. affinis* burrows in muddier sediments than does *Callianassa* and prefers slightly lower salinities and less current energy, although their bathymetric ranges are comparable. These conditions are found commonly along salt marsh tidal stream or estuary banks and in muddy point bars and tidal flats, as well as in relatively shallow lagoonal or estuarine mud bottoms.

Some Lee Creek specimens of *Thalassinoides* possibly were constructed by the snapping shrimp *Alpheus heterochaelis*, although the characteristic anastomosing-downward pattern of its burrows (Basan and Frey, 1977) was not observed. The environmental range of *A. heterochaelis* broadly overlaps that of *Upogebia affinis* (Howard and Frey, 1975).

Another trace fossil that merits special attention is *Skolithos*. Several worms living along the present southeastern Atlantic coast construct *Skolithos*-like dwelling tubes (e.g., Hertweck, 1972), and some minor variations were noted among our Pleistocene specimens. But most *Skolithos* observed by Curran and Frey (1977) were extremely similar to dwelling tubes of the polychaete *Onuphis* (Howard and Frey, 1975, 1980a, 1980c). Environments inhabited by *Onuphis* are generally similar to those preferred by *Callianassa biformis*, overlapping those of *C. major*; yet the polychaete avoids higher energy levels. It is found commonly in estuarine point bars, tidal flats, relatively shallow channel bottoms, and low-energy beach and nearshore environments (Howard and Dörjes, 1972), but not in purer muds, such as those typically occupied by *Upogebia*.

Occurrence of these trace fossils in the Lee Creek section is compatible with the kinds of sediments and sedimentary structures associated

today with their extant counterparts (Howard and Frey, 1980c), yielding a powerful additional dimension to our overall study. Furthermore, biogenic sedimentary structures, unlike tests and shells, are enhanced by diagenesis and ordinarily cannot be reworked or transported into other depositional environments (Frey, 1975; Frey and Seilacher, 1980); if reworked, they are easily recognized as such (Figure 13).

## Descriptions of Stratigraphic Units

### Yorktown Formation

The Yorktown (probably lower or middle Pliocene; DuBar and DuBar, 1980) lies beneath the Upper Shell unit (lowest Pleistocene, or possibly upper Pliocene; Blackwelder and Ward, in prep.). Both the Yorktown and the Upper Shell unit, although not studied in detail, are included here for the sake of continuity. Average thickness of the Yorktown, as measured by us, is 45 feet (14 m); the upper 10 feet (3 m) or less is referred to locally as the "Boulder" bed. This bed, possibly a result of post-Yorktown weathering, together with striking faunal changes in the overlying Upper Shell unit, constitutes major evidence within the pit for an unconformity between the Yorktown and overlying units, although not recognized by Gibson (1967). Evidence presented by Welby (1971) and Wheeler, Daniels, and Gamble (this volume) indicates that the upper part of the Yorktown is partially cemented by carbonate to form irregular concretionary masses up to 3 feet (90 cm) across, a feature well expressed throughout eastern North Carolina at this stratigraphic position. Apart from these concretionary masses, the Upper Shell unit typically overlies the Yorktown with sharp, although in some places gradational, contact. This contact apparently was planar where we observed it (i.e., no irregularities).

The upper 10 feet (3 m) of the Yorktown consists of fine- to coarse-grained, muddy, subangular to subrounded quartz sand and glauconite. The color of the unit ranges from medium and light gray to dark brown and orange, where stained with iron oxide. No shells or bones were found, but the entire sequence is intensely bioturbated. The trace fossil *Ophiomorpha nodosa* is present, although rare; these small, somewhat irregular specimens may correspond to burrows of *Callianassa biformis* (Hertweck, 1972; Howard and Dörjes, 1972; Howard and Frey, 1975; Frey, Howard, and Pryor, 1978). Bedding in the unit is obscured by bioturbation and selective lithification.

The environment of deposition of the upper Yorktown presumably was one of nearshore, shallow marine water, although the quantity of mud matrix suggests a moderate rather than a high-energy regime. A more refined analysis depends on studies of Yorktown facies elsewhere, and their environmental interpretation.

### Upper Shell Unit

The Upper Shell unit is now generally regarded as post-Yorktown, although authors differ as to formational assignment (Gibson; Hazel; Curran and Parker, all this volume; DuBar, Solliday, and Howard, 1974:109; Bailey, 1977; and Blackwelder and Ward, in prep.). The unit is characterized by large molluscan shells. Faunal lists (Parker, 1972; Blackwelder and Ward, in prep.) consist of 95 species of bivalves, 97 species of gastropods, one species of scaphopod, 3 species of corals, an undetermined number of bryozoans, echinoids, barnacles, crabs, and a hydrozoan. The matrix around shells, many of which are tightly packed, is fine- to medium-grained quartz sand, generally containing minor amounts of silt and clay; the percentage of silt and clay increases greatly in some places.

The unit ranges from 2 to 10 feet (0.6 to 3 m) in thickness, although in one area it was entirely removed by erosion prior to deposition of the overlying unit (Figure 4, trench IV). Upper and lower contacts appear to be unconformable, more pronounced relief being visible on the upper contact; the Shell Hash unit overlies the Upper Shell unit with obvious relief and a sharp contact in most places.

Distinct horizontal bedding (in most places),

densely packed shells, many of them articulated, and successive changes in faunal assemblages from the lower to the upper part of the unit (Curran and Parker, this volume) suggest repeated catastrophic "kills" and normal salinity at the base, shifting to lowered salinity at the top. Sandy clay plugs in the outermost whorl of large *Busycon* snail shells commonly entrap clean-washed shell hash and quartz sand within inner whorls. This sediment contrast suggests that either (1) such shells were transported from a high-energy environment containing little mud into one in which mud was a common constituent, or (2) by a change in depositional regimes, mud was brought into the environment and settled between large shells. The high percentage of unabraded, articulated bivalves (Curran and Parker, this volume) indicates general absence of shell transport. Thus, periodic influx of mud, possibly delivered by riverine estuaries following torrential rains in the hinterland, together with correspondingly abrupt decreases in salinity, may account for the catastrophic death assemblages. Variations in wave energy, such as those induced by small-scale storms, perhaps enhanced horizontal bedding and shell concentrations.

Sediments through the entire thickness of the Upper Shell unit along the northern edge of the pit exposure are cross-bedded. Here, shells from lower and upper assemblages are mixed thoroughly. The cross-beds include both tabular (up to 6 ft, 1.8 m, thick) and trough sets (less than 2 ft, 60 cm, thick). We interpret this occurrence as local reworking and redeposition of sediments of the entire unit, possibly by means of an estuarine channel or estuary-entrance scour hole (Frey, Voorhies, and Howard, 1975; Howard and Frey, 1980c, fig. 14). The reworking may be related to erosion just prior to deposition of sediments of the Shell Hash unit, in which case the cross-bedded debris would probably be placed in the Shell Hash unit.

The change in faunal assemblages from the base to the top of the unit suggests a change in salinity and/or a change to predominantly intertidal exposure; lower zones contain a high-diversity fauna of mollusks, corals, echinoids, etc., whereas subsequent assemblages grade into an upper zone characterized by *Geukensia* species and *Ostrea meridionalis*. *Geukensia* is indicative of slightly lower salinities and shallow subtidal to intertidal environments (Basan and Frey, 1977:55, 64, 65); the same seems to be true of *O. meridionalis* (Curran and Parker, this volume). Thus, the Upper Shell unit probably shows normal salinities in its lower part and somewhat decreased salinities and/or increased subaerial exposure in its upper part. Postulated periodic "kills" by lowered salinities and mud suggest proximity to a terrigenous sediment supply. These combinations of effects suggest an open estuary mouth or adjacent nearshore-shelf environment for the base of the unit, with perhaps moderate water depths (cf. Frey and Pinet, 1978), grading upward to shallower, less saline waters of the middle reaches of an estuary. Ultimately, the sea regressed and deposits of the Upper Shell unit were channeled by erosion.

### Shell Hash Unit

The Shell Hash unit consists of poorly sorted, coarse- to fine-grained quartz sand, broken and current-worn invertebrate (mostly molluscan) shells of diverse sizes, mud clasts, and woody debris. It varies in thickness from several inches (centimeters) to 4 feet (1.2 m). The shells (only a few of which are whole, single valves) were derived from the underlying Upper Shell unit when, following erosion of the latter, the sea again entered the area. Shelly debris generally forms less than 50 percent of the deposit.

The Shell Hash unit commonly is trough cross-bedded, although gently inclined bedding also is found (Figure 5). Trough sets generally are less than 1 foot (30 cm) thick. *Skolithos linearis* is abundant locally; *Ophiomorpha nodosa* is present, although not common. Sediment sorting (Folk, 1974:3–7, 15–48; definition and methodology) in bulk samples is poor (1.25 to 1.86 $\phi$); mean grain sizes range from coarse to fine sand (0.90 to 2.15 $\phi$). If the quartz matrix alone is sampled (neglecting shells and mud clasts), sorting is very good to moderate.

This unit overlies the irregular surface of the Upper Shell unit and interfingers laterally with, and grades vertically into, the Mud and Sand unit. Molds of broken-shell debris in the base of the latter (shells are leached out in more acidic mud) apparently support this conclusion, although proper taxonomic designations were not established. For these reasons, the Shell Hash unit tentatively is considered to be related genetically to the Mud and Sand unit (see Figure 4 for lateral relationships).

A high-energy depositional environment is indicated by ripped-up mud clasts, trough cross-beds, moderate sorting, and the common occur-

FIGURE 5.—Epoxy relief peel of cross-beds and ripple laminae in Shell Hash unit. Mud chips occur in lower half, where shell debris is abundant. Trench II, section 1 of Welch (1972). Scale in millimeters.

rence of coarse-sand and fine-pebble grain sizes together with the worn and broken molluscan shells. Such facies are developed today within and adjacent to estuarine channels and estuary-inlet shoals on the nearshore shelf of Georgia (Oertel, 1973; Howard and Frey, 1980c, figs. 10, 13, 14), and can include tubes of *Onuphis microcephala* (*Skolithos* analog) and burrows of *Callianassa major* (*Ophiomorpha* analog).

Faunal evidence for the depositional environment of the Shell Hash unit consists of what initially may appear to be an anomalous association of well-preserved valves of *Corbicula densata*, a brackish water bivalve, with *Skolithos linearis* and *Ophiomorpha nodosa*, trace fossils most often associated with conditions of near-normal to normal salinity. However, species of the genus *Corbicula* are noted for their ability to tolerate a range of lowered salinity to freshwater conditions and apparently can exist for extended periods under either brackish or freshwater conditions (Evans et al., 1979:194, 212). Howard and Frey (1975:53, 55) have shown that the organisms that form *S. linearis* and *O. nodosa* burrows (especially *Callianassa biformis*) commonly inhabit the shallower, sandy parts of Georgia estuaries and can tolerate salinities as low as 10 ‰, at least for short periods. Thus, this faunal association of the Shell Hash unit, rather than being anomalous, seems to be indicative of estuarine conditions during deposition.

### Mud and Sand Unit

The Mud and Sand unit in places contains diverse sediments, including boulder-sized rock clasts, but most lithologies fall within two distinctive members: (1) a dark gray to dark greenish gray, sandy clay member, and (2) a clay-mottled, tan sand member. The two members interfinger irregularly, some sections consisting entirely of one or the other member and other sections containing various combinations of the two. Details of the complex interrelationships between members have not been determined, although these would have considerable environmental significance. In general, the sand member has diffuse boundaries but forms an irregular tongue within the mud member (Figure 4).

Thickness of the entire Mud and Sand unit ranges from 1 to 16 feet (0.3 to 5 m), due mainly to the irregular topography upon which it and sediments of the Shell Hash unit were deposited; another factor is higher elevation, with respect to present sea level, of the upper contact on the north side (trenches I, II, Figure 4) than on the south side of the pit (trenches III, IV, V). This difference (approximately 5 ft; 1.5 m) is believed to have resulted from erosion occurring after deposition of sediments of the Mud and Sand unit but prior to deposition of sediments in the overlying Current unit.

In the region where the Mud and Sand unit has been eroded most deeply (trenches IV, V, Figure 4), pebbles, cobbles, and boulders are most abundant and lie on top of the entire unit. These clasts are rounded and show a variety of shapes, from equant to discoid and rod-like. Almost all clasts have a gneissic and quartzitic composition; one gneissic boulder measured more than 1 foot (30 cm) in its longest dimension, and weighed more than 50 pounds (22.5 kg). The nearest outcrop of these lithologies is in the Piedmont, 100 mi (160 km) to the west. None of these clasts was seen to penetrate into the top of the Mud and Sand unit; hence, they are considered to have lain on a hardened mud surface after the mud was compacted and, in our opinion, after erosion of that unit. Only a few small pebbles were found on top of the Mud and Sand unit outside the region of maximum erosion (trenches I, II, Figure 4); we conclude that maximum scour, maximum clast size, and highest concentration of clasts occur in the same area. In addition to clasts, Blackwelder and Ward (in prep.) reported rooted tree stumps at the top of what we consider to be the Mud and Sand unit.

The clay-mottled sand member of the Mud and Sand unit forms an irregular tongue. Clay mottling results from intense bioturbation of mud-draped ripples and cross-beds. Thorough bioturbation of interbedded sand and mud layers, or of wavy, lenticular, and flaser bedding, in fact commonly produces a gross mixture of biotur-

bated muddy sand (Howard and Frey, 1980a:174, 1980c:121). Clay-lined *Ophiomorpha nodosa* is abundant (Figure 6); *Skolithos linearis* is less so. Other bioturbation structures are common but are less distinctive (Curran and Frey, 1977). "Sitz marks" (possibly bivalve and anemone resting and escape traces; Frey and Howard, 1972) and physical collapse structures (Frey, Howard, and Pryor, figs. 7e, 9) also are common. The top of the unit is everywhere the sandy mud member, and in trench II (Figure 4) it is riddled with *Skolithos linearis*, possibly indicating a fairly coherent substrate (cf. Frey and Howard, 1969, pl. 2: fig. 2; Howard, Frey, and Reineck, 1973:40) related to conditions of the overlying Current unit (Figure 7).

The clay-mottled sand member of the Mud and Sand unit contains ripples and cross-beds in tan quartz sand, and these are commonly draped with dark gray mud. Mud-draped ripples, termed "flasers" (Reineck and Wunderlich, 1968) are considered by many authors to be strictly intertidal in origin (Klein, 1971, table 1), although they are abundant subtidally within estuaries, the nearshore shelf, and inlet-shoal complexes in Georgia waters (Oertel, 1973; Howard and Frey, 1973, 1975, 1980a, 1980c). Flasers suggest tidal oscillations in energy of transportation and deposition of sediments, whether in intertidal or subtidal environments. In addition, many clay wisps and flasers are the result of fecal-pellet deposition, the pellets behaving hydrodynamically more as

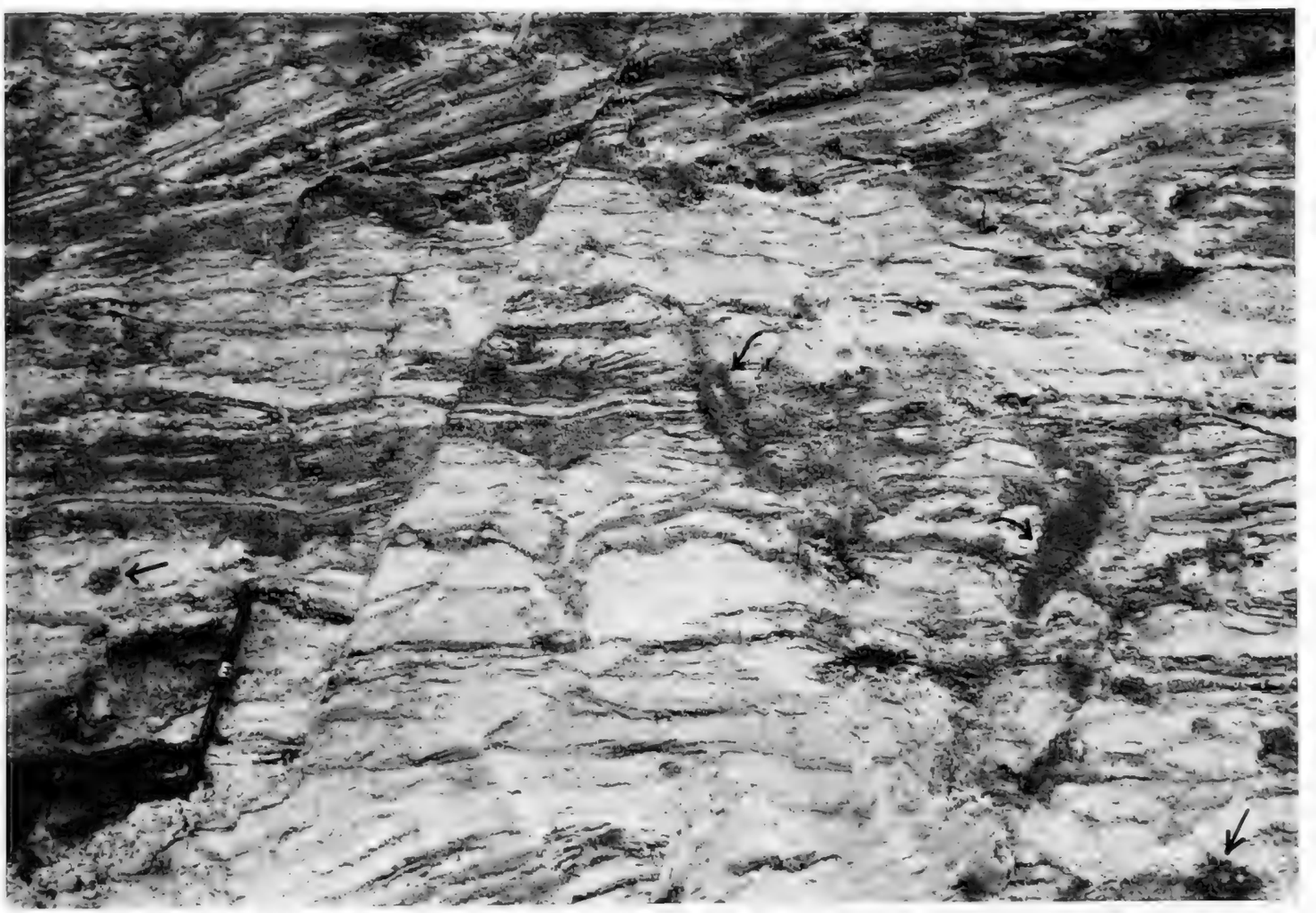

FIGURE 6.—Clay-mottled sand member of Mud and Sand unit. Rippled sand in both wavy bed and flaser structure is modified by bioturbate textures and post-depositional fault. Arrows indicate *Ophiomorpha nodosa*, some sections being diagonal to face of exposure, Trench III, 1971. No faults observed in beds younger than Current unit.

FIGURE 7.—Contact of Mud and Sand unit (lower one-third) with Current unit (upper two-thirds). Vertical tubes (*Skolithos linearis*) just below pen penetrate top of Mud and Sand unit and also occur in lower part of Current unit, here containing scattered clay wisps. Trench II, near section 1 of Welch (1972).

sand than as discrete or flocculated particles of clay during transport and deposition; thus, contrary to previous views of clayey sediments as the result of deposition of suspended sediments under quiet-water conditions, fecal mud is easily accumulated under conditions of moderate, persistent wave and current energy (Pryor, 1975). When pellets are compacted after burial, they become indistinguishable from other muds deposited physically or electrolytically in shallow nearshore or back-barrier environments (Frey and Basan, 1978:139–141). Linsen beds (sand ripples, one ripple-layer thick, surrounded by mud) also are reported from tidal flats (Reineck and Wunderlich, 1968) and subtidally from Georgia estuaries (Oertel, 1973; Howard and Frey, 1973, 1975, 1980a, 1980c).

Size analyses of seven samples from the clay-mottled sand member indicate that it generally is poorly sorted, fine- to medium-grained sand, although moderately well-sorted coarse sand also was found (Figure 8). Mean grain sizes of the dominant group ranged from 1.75 to 2.70 $\phi$ and the standard deviation from 0.98 to 1.41 $\phi$. The sandy mud member consists of very stiff, dark gray to dark greenish gray clay having thin coarse sand layers, ripple (linsen) sand layers, and small isolated pebbles. The clay in places includes laminae of sand less than 0.06 inches (2 mm) thick (Figure 9) that alternate with thicker mud layers. In general, however, the clay has an unstructured appearance which, upon closer inspection, shows profuse bioturbate textures. The most common

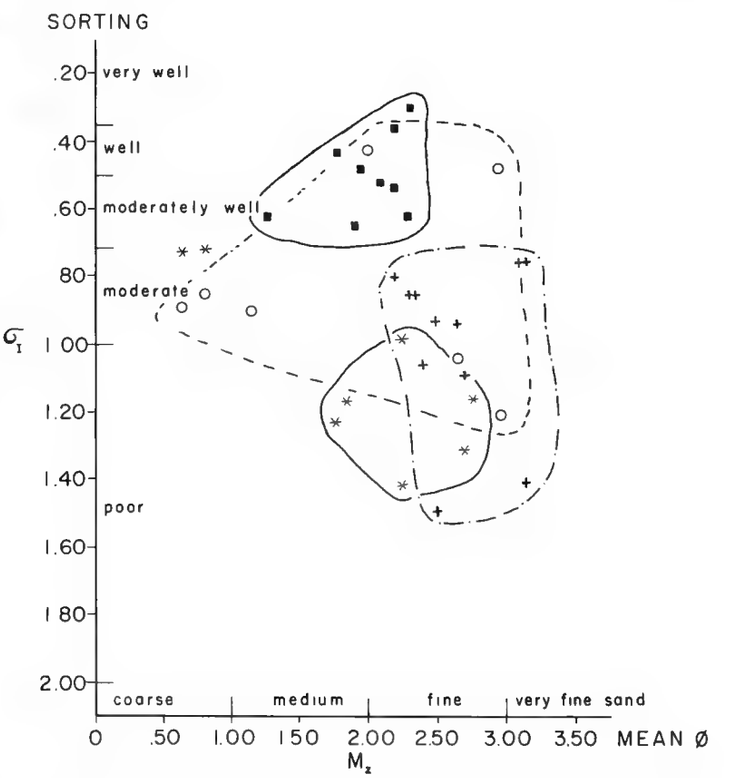


FIGURE 8.—Grain-size analysis of sediments. (35 samples taken in 1971 and 1972 from sections measured.) Black square is tabular cross-bed member of Current unit; circle is Channel unit; cross is Mottled unit; star is sand member of Mud and Sand unit. Except for sand member of Mud and Sand unit, all sediments lie within compact area (graphical mean (Mz) in $\phi$ units plotted against graphical standard deviation ($\sigma_I$); Folk, 1974).

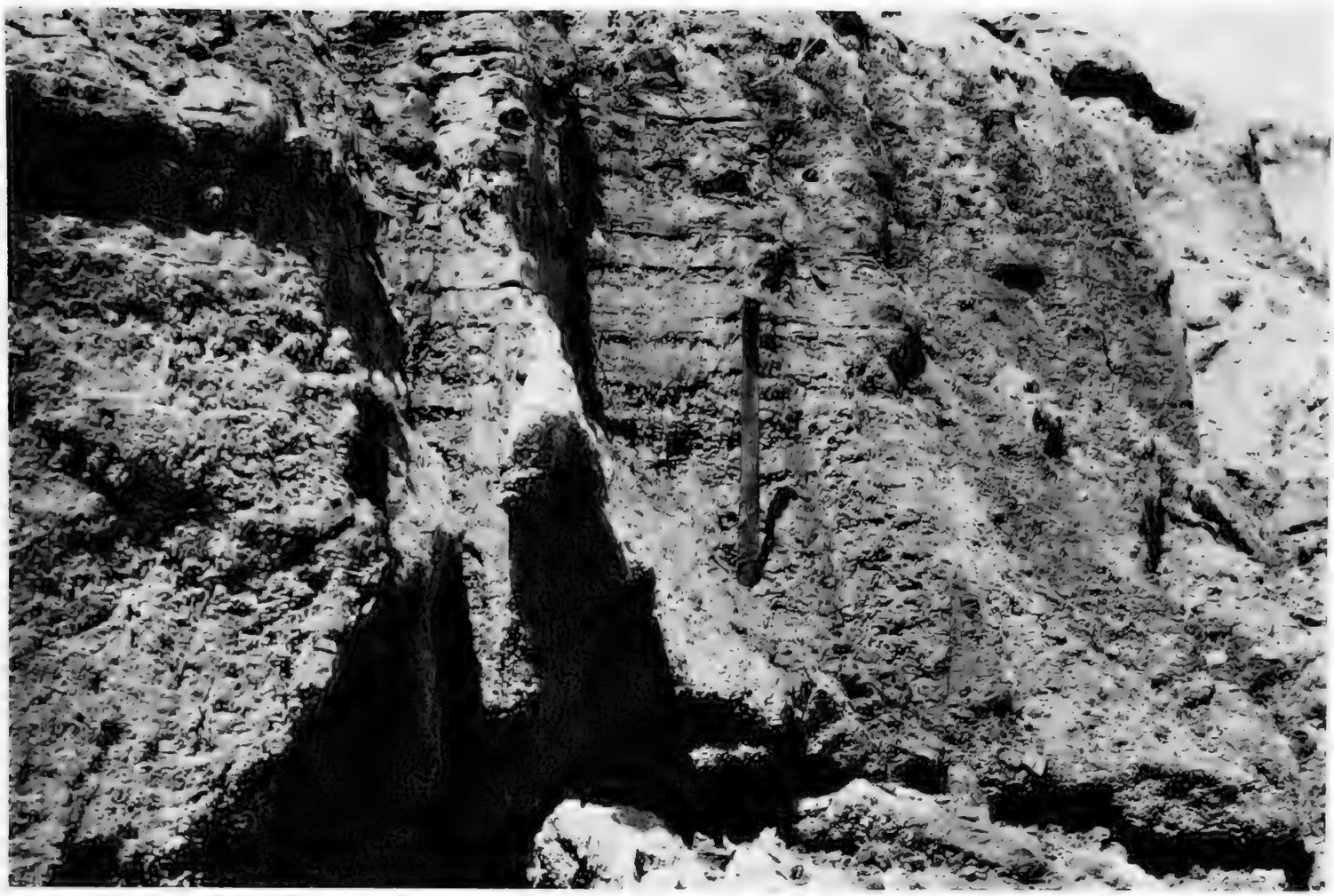

FIGURE 9.—Laminated upper part of Mud and Sand unit. South wall, Trench II, 1971. Machete blade approximately 1.2 feet (35 cm) long. (Photo by James Austin.)

burrow structure is *Thalassinoides* species; it consists of a clay-lined dichotomous tunnel that became filled with clay-rich to clean-washed sand and organic matter once the burrow was abandoned. Other types of biogenic structures (Curran and Frey, 1977:151) resemble bioturbate textures produced by capitellid polychaetes in Georgia estuaries (Howard and Frey, 1973:1182; 1975:51–62; 1980a, fig. 6.11).

Physical and biogenic sedimentary structures of the Mud and Sand unit suggest complex interfingering of a normal or nearly normal salinity, relatively high-energy depositional environment (clay-mottled sand member containing *Ophiomorpha nodosa* and *Skolithos linearis*) with a fairly low-energy, perhaps less saline, muddy environment (sandy mud member having *Thalassinoides* species). We thus consider the sand member to represent a subtidal channel or muddy point bar deposit in an estuary that had free access to seawater of normal salinity, and the mud member to represent a subtidal and/or tidal flat environment within an estuary possibly somewhat farther removed from constant access to normal salinities.

The entire Mud and Sand unit might represent part of a subtidal estuary complex having more freshwater influences near the margins, the deeper channel carrying greater quantities of sand and possessing more nearly normal salinities (Hayes, 1975:11; Meade, 1972). Equally plausible, however, is a salt marsh estuary (without an active river at its head) such as Doboy Sound, Georgia (Mayou and Howard, 1975:212); there, mud is abundant in the deeper part of the channel but becomes decreasingly important toward the shallower lateral margins of the estuary (Howard

and Frey, 1980a). Salinities are comparable throughout, but differences in energy levels and substrate characteristics greatly modify distributions of infaunal organisms. Ideally, estuaries having active rivers at their head would accumulate much more sand; in most Georgia estuaries, however, the facies pattern of riverine and salt marsh estuaries is so modified by local sand sources that the two might not be distinguishable in the rock record (Howard and Frey, 1980c:103). Detailed interpretation of these, and the two members of the Mud and Sand unit, requires excellent stratigraphic control and thorough documentation of lateral relationships among sediment bodies.

Upright tree stumps at the top of the Mud and Sand unit indicate a shoaling of the sea just prior to development of an erosional surface that included a channel cut into the top of the unit. A log recovered from the base of the unit in trench IV (Welch, 1972:2, appendix), contained the hole of a boring bivalve (possibly a pholad), and yielded a $^{14}C$ date (Teledyne Isotopes, Inc., no. 1-6621) greater than 40,000 years BP.

## Current Unit

The Current unit is divided into two members: (1) the tabular cross-bed member (lower), and (2) the wavy bedded member (upper). Total thickness of the unit ranges from 4 feet (1.2 m) in trench I (Figure 4) to 15 feet (4.7 m) in trench V. It rests unconformably on the Mud and Sand unit, and fills low places of irregular relief developed on it. The upper contact, as near as we can measure it with a transit, is nearly horizontal and almost at present mean sea level.

At one place or another, the Current unit is overlain unconformably by a variety of units. In trenches IV and III, it is almost completely removed by erosion and is overlain by the Channel unit (Figure 4). In trenches V, II, and I, it is overlain either by discontinuous peaty lenses of the Peat and Clay unit, or by the Mottled unit. This unconformity shows more relief than any other observed in the section, although its relief does not necessarily mean that it is correspondingly more profound; the time interval represented by any one of the unconformities described herein remains unknown (Table 1).

The tabular cross-bed member of the Current unit is the thicker member, ranging from 3 to 10 feet (0.9 to 3 m). It consists of tan, subangular to subrounded, fine- to medium-grained (1.25 to 2.31 $\phi$), well sorted (0.30 to 0.65 $\phi$) quartz sand. Minor amounts of feldspar, mica, and heavy minerals are found. All samples plot in a surprisingly close cluster (Figure 8), a distinguishing characteristic.

The member contains well-developed tabular (planar) cross-beds (Figure 10), in sets that range in thickness from 1 to 5 feet (0.3 to 1.5 m), in exposures on the west end of the pit. Each set, as well as each lamina of foresets, typically is separated or delineated by heavy minerals or by light brown silty sand, some by muddy sand. The sets appear to be graded. This feature was noted by Terwindt (1971:517), Greer (1975:117), Howard and Frey (1975:41, 1980a:162, 1980c), Frey and Howard (1980:192–193), and Visser (1980) among modern subtidal and intertidal estuarine sands deposited by ebb-dominant currents that produced tabular to trough cross-bedded sets. Flood-oriented cross-beds are rare along the Georgia coast; they are not so rare within relict flood tidal deltas (Belt, 1970:15; Boothroyd, 1978:329–336). Although some authors consider unidirectional features unlikely (Klein, 1971) or at least remarkable in a bidirectional tidal system (Terwindt, 1971:518), ebb-current dominance in estuaries is typical of the southeastern U.S. coast. Here, pronounced inequities of tidal flow result from frictional drag by marsh grasses during early ebb, followed by dramatically accelerated ebb flow down the estuarine water slope once the marshes have been drained (Howard and Frey, 1980a:156–161, 1980c:93). Such retardation, then acceleration along a steep pressure of hydraulic gradient, does not occur during tidal flood.

Tabular cross-beds in the western exposure of the Current unit present a remarkably uniform dispersion of paleocurrent directions (Figure 11); a mode trending to the east-northeast is consistent with an ebb orientation. A few trough cross-beds and current-rippled laminae are found in the

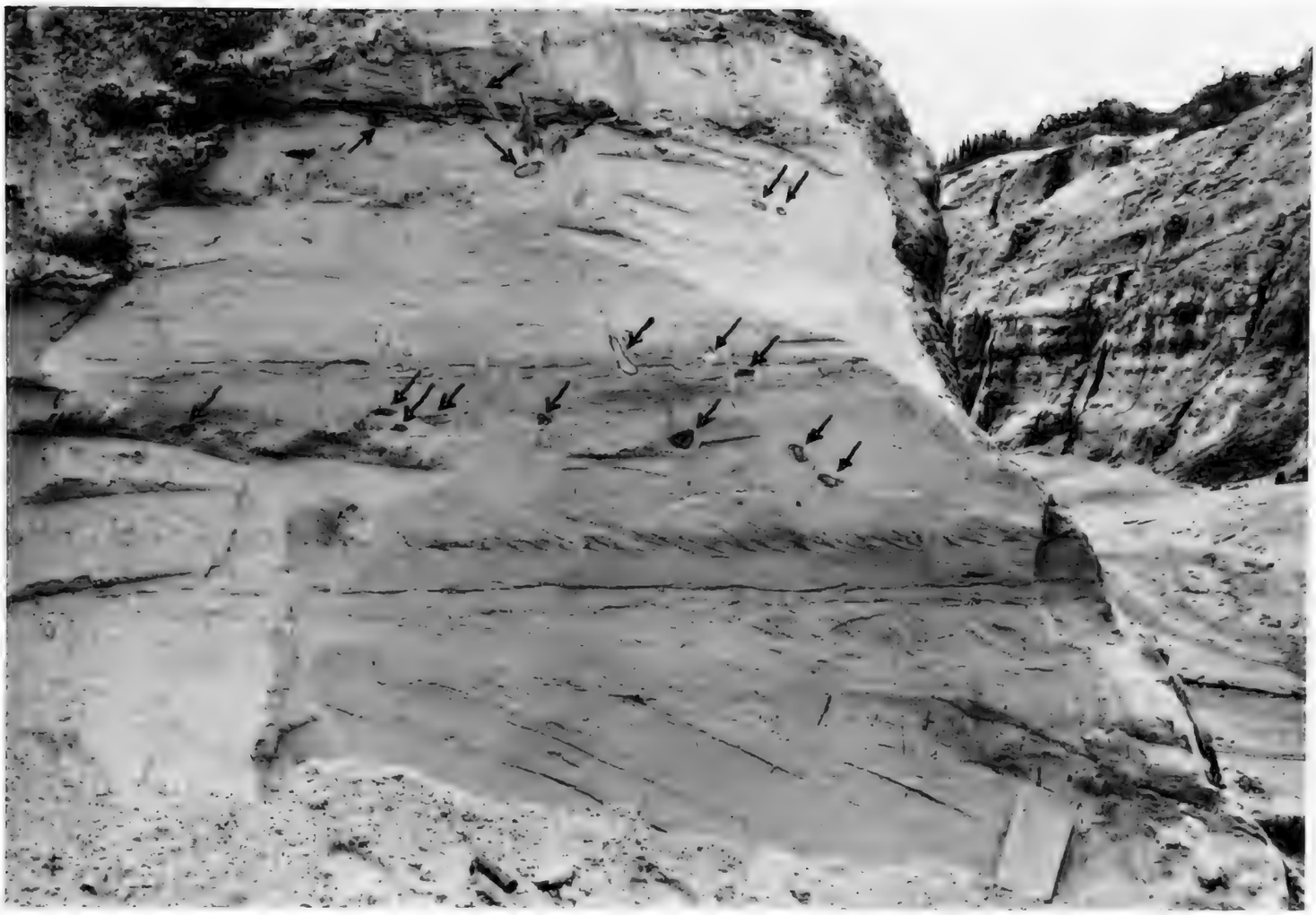

FIGURE 10.—Tabular cross-bed member of Current unit. Cross-bed sets trend northeast, some separated by ripple-laminated sand. Arrows indicate *Ophiomorpha nodosa*, abundant in upper part of unit. Faint vertical lines near field notebook are clay-filled *Skolithos linearis*. U- and V-shaped irregularities in certain laminae are "sitz marks." Heavy minerals and organic debris or silty clay distinguish bedding and laminae. Trench V, south wall, 1971.

exposures on the west end of the pit, but the entire Current unit is trough cross-bedded on the east end of the pit (Figure 14). This feature, tabular cross-beds having silt layers at the top of each lamina, grading into trough cross-beds down an estuary, was observed in Lower Cretaceous estuarine sands by Campbell and Oaks (1973) and in modern estuaries (Terwindt, 1971; Greer, 1975; Howard and Frey 1975, 1980a, 1980c; Frey and Howard, 1980; Visser, 1980).

The most spectacular sedimentary structure in the tabular cross-bed member consists of V- to U-shaped nested laminae in a cylindrical column up to 10 inches (24 cm) in diameter; the largest one extended through the entire thickness of the Current unit (10 ft or 3 m), in a near-vertical position, penetrating the top of the Mud and Sand unit. The structure apparently was not affected either by sand avalanches of tabular cross-beds or by the change in depositional environment from the tabular cross-bed member to the wavy bed member of the Current unit. Its origin remains problematical (Bromley et al., 1975:366–369; Curran and Frey, 1977:142).

Biogenic sedimentary structures are common in the tabular cross-bed member (although they are even more abundant in the overlying wavy bedded member). The three most common lebensspuren are *Ophiomorpha nodosa*, *Skolithos linearis*, and "sitz marks" (Figure 10). However, some of these deep V- to U-shaped laminated structures (Figure 12) are the result of collapse of

overlying sand into open burrows (*Ophiomorpha*), as described by Frey, Howard, and Pryor (1978). The smaller nested structures are interpreted as escape burrows of animals having anemone-like behavior (Curran and Frey, 1977:142). Another structure, a sediment-filled depression about 2 feet (60 cm) in width, is most likely a feeding trace of a large sting ray (cf. Frey and Howard, 1969, pl. 3: fig. 5; Howard and Frey, 1975, 1980c, fig. 20). Finally, small (less than 1 in, 2 cm, typically) to very small (a few millimeters in size) V-shaped "kinks" are common in tabular foresets (Figure 10). These may be escape traces of small arthropods (mole crabs, etc.) and/or bivalves, such as *Donax* or *Mulinia* (Frey and Howard, 1972).

The assemblage of physical and biogenic structures, taken as a whole, indicates a moderate to high-energy environment of rapidly shifting sands (and perhaps a faint reverse tidal flow, suggested by the graded thin silt and clay layers between sets and foresets), representing avalanche lobes or megaripples migrating with the dominant current direction, presumably tidal ebb, and normal or nearly normal salinity. No structures that could be assigned to reactivation surfaces (microerosion produced by tides; Klein, 1970:1118) were seen. The environments of the cross-bed member most probably were shallow subtidal to intertidal, evidently a point bar sequence.

Recent estuarine point bars of coastal Georgia and South Carolina are elongated parallel with the axis of tidal streams (Barwis, 1978:140; Frey and Howard, 1980, fig. 7.1; Howard and Frey, 1980a, fig. 6.4, 1980c:111–114). The sand bodies are divided longitudinally into two subfacies: the exposed, channelward side consists of relatively clean, graded or ungraded, megarippled to ripple-laminated sand, deposited under moderately high energy, whereas the more protected, marshward side consists of cross- or wavy-laminated muddy sand and mud deposited under lower energy conditions (Howard, Frey, and Reineck, 1973). Migrations of bars produce large curving foresets having amplitudes of 28 inches (70 cm) to more than 3 feet (1 m). Closely adjacent, shallow subtidal deposits are similar, essentially being subaqueous extensions of the bars. In broader estuaries, given an ample sediment supply, one would expect correspondingly broader sediment bodies, grading into high-energy sand flats or shoals and low-energy "mud flats," where the tidal range is high (Hayes, 1975), or into zigzag shoals within a place of moderate tidal range (Ludwick, 1974, fig. 7). A barrier island inlet system (Hubbard, Oertel, and Nummedal, 1979) is not postulated for this member, chiefly because evidence of the barrier itself is lacking.

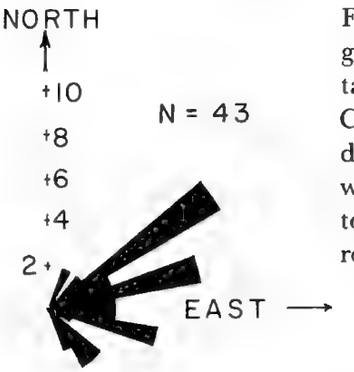


FIGURE 11.—Azimuthal histogram of foreset dip directions in tabular cross-bed member of Current unit. Scale (2–10) indicates number of readings within each 10-degree class interval. N equals total number of readings.

The tabular member is thinner to the north than to the south (Figure 4) and, as mentioned previously, is trough cross-bedded and thinner to the east. Perhaps the mine trenches had not uncovered the lateral equivalent of a muddy subfacies at the level of the tabular member. More likely, a muddy subfacies appears in the sequence as the overlying flaser beds, when the depositional centers shifted gradually with time; nevertheless, the geometry of the sand body itself seems to be one of a large equant lens, possibly reflecting either a large point bar or migrating small point bar.

The wavy bedded member of the Current unit (Figure 12) is conformable above the tabular cross-bed member and consists of horizontal and ripple-laminated sand layers having mud drapes (wavy and flaser beds; Reineck and Wunderlich, 1968). The sand is fine to medium grained (1.60 to 2.03 $\phi$), poorly sorted (1.12 to 1.15 $\phi$), and would plot within or close to the cluster represented by the Mud and Sand unit (Figure 8). The proportion of mud to sand changes markedly from one trench to the next, however. This member attains a thickness of 1 to 5 feet (0.3 to 1.5 m), thinning gradually to the north.

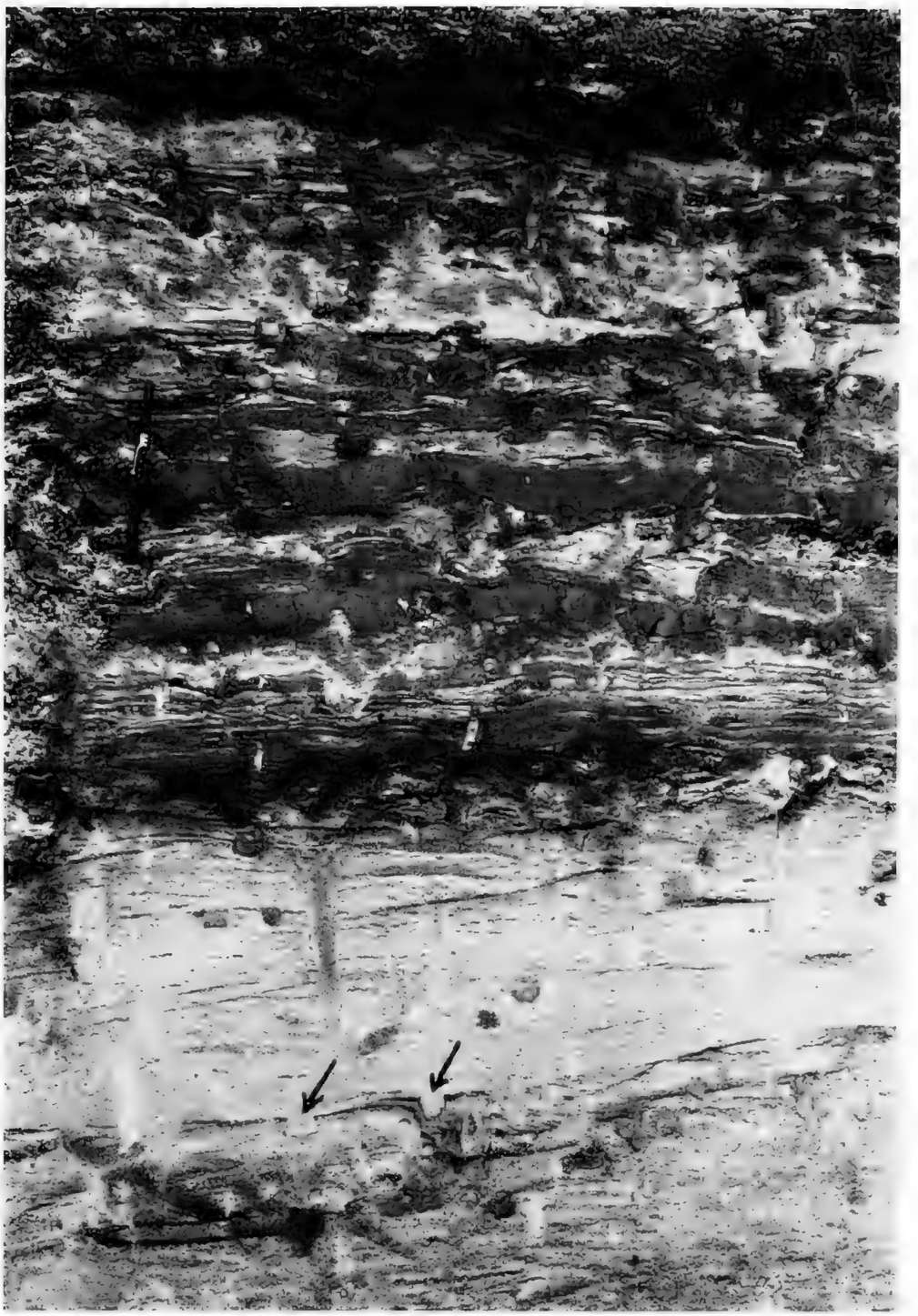

FIGURE 12.—Wavy bedded member of Current unit (upper two-thirds), showing flasers and mud layers. Box-shaped depressions (arrows) in heavy mineral layer in underlying tabular cross-bed member probably represent sediment collapse into *Ophiomorpha nodosa* below (horizontal clay-lined tube). Deep furrow above left arrow also may be a collapse structure, although small anemones make similar looking escape structures. Trench V, east end of north wall, 1971.

Bioturbation was moderate to intense, and a wide variety of biogenic structures was found. The structures include easily recognizable *Ophiomorpha nodosa*, *Skolithos linearis*, and "sitz marks"; many others, less easily recognized, also are present. Most *Ophiomorpha* in the upper part of the tabular cross-bed member originated from the horizon of the wavy bedded member. *Callianassa major* is known to penetrate downward 10 to 12 or more feet (3 to 4 m) into beaches along the coast of Georgia today (Frey, Howard, and Pryor, 1978).

Mud drapes (wavy and flaser beds) over current-rippled sand suggest a tidal influence and marked fluctuation in energy levels within the depositional environment (Howard and Frey, 1980a). Some mud wisps in ripple troughs probably represent accumulations of fecal pellets; the polychaete *Onuphis* and the shrimp *Callianassa* (analogs for the Pleistocene animals constructing *Skolithos* and *Ophiomorpha*, respectively) contribute large quantities of fecal pellets today that are washed into and preserved within ripple troughs (Oertel, 1973; Pryor, 1975; Frey and Howard, 1980; Howard and Frey, 1980a, 1980c). The moderate to intense degree of bioturbation suggests moderately low depositional rates (in contrast to relatively rapid rates for the underlying tabular cross-bed member). Salinity was normal or nearly normal, based upon modern analogs of the biogenic structures. Hence, either the water became deeper, in which case the wavy and flaser-bedded sand might correspond to the shallow subtidal part of the "estuarine accretionary beds" of Howard and Frey (1980b); or, the water became shallower or remained at essentially the same depth, the deposit corresponding to an intermediate-energy upper point bar facies or tidal flat adjacent to or overlapping the depocenter for the tabular member. We suggest a fining-upward point bar sequence, possibly spillover lobes filling a multilobed bar margin (Barwis, 1978).

Thus, during deposition of sediments of the Current unit, avalanche deposits of clean-washed sand first were laid down in waters of moderate to shallow depth (a few 10's of feet, ~10 m, at most; probably less) in an estuary dominated by ebb currents. The water then shoaled, by upbuilding of point bars and related features, and/or by a eustatic drop in sea level. If we accept the eustatic hypothesis, it may have been the first stage in the general eustatic drop that culminated in erosion into the Current, and Mud and Sand units (Figure 4, trenches IV, III).

### Channel Unit

The Channel unit varies in thickness from zero to 11 feet (3.3 m) and consists of light-gray to white and tan, coarse- to fine-grained, predominantly subangular to subrounded, quartz sand. Minor amounts of heavy minerals, where present, define ripple laminae and trough cross-beds, the latter being the dominant sedimentary structure in the unit (Figure 13). Trough cross-bed sets are 2 to 3 feet (60 to 90 cm) thick; wave lengths are estimated at 6 to 8 feet (1.8 to 2.4 m). Mud clasts up to 6 inches (15 cm) in size indicate (1) the erosion of compacted mud, possibly from the Mud and Sand unit and (2) excavation and transport of pieces of clay-lined *Ophiomorpha*. Woody debris, twigs, and a large log were found. Streaks of black organic matter commonly accentuate cross-bed laminae. The range of grain size and sorting for the Channel unit is greatest of any sand unit studied. Although only a few samples were analyzed, they were selected in order to accentuate the differences. Hence, poorly sorted fine sand, moderately sorted coarse sand, and well sorted fine- to medium-grained sand were found; the field of mean sizes (Figure 8) overlaps those of the Current, Mottled, and Mud and Sand units.

Channel unit sands fill a wedge-shaped cut that pinches out to the north, south, and west. The cut penetrated the upper part of the Mud and Sand unit in trench IV (Figure 4), and originally may have cut down even farther; but mining had (by 1971) removed much of the evidence to the east. The clay plug seen 1 mile (1.6 km) to the east (east wall of pit; Figure 14) may have been part of the same channel network; it seems to be located in the same stratigraphic position as the Channel unit, between the Current

FIGURE 13.—Channel unit, showing large-scale trough cross-beds. Mud clasts (some of which are fragmented, reworked *Ophiomorpha nodosa*) accumulated along single horizon (arrow). Dark layer at base, near field notebook, is part of Mud and Sand unit, clasts of which are incorporated into lower part of Channel unit. West end of Trench IV, near section 4 of Welch (1972).

FIGURE 14.—Clay plug, probable remnant of Peat and Clay unit, and relationships of Mud and Sand unit and Current unit. Mottled unit, not recognized here, may have been removed by mining or obscured within highly oxidized upper few feet (meters) of section. East wall, Lee Creek Mine, 1972. (Photo by James Austin.)

unit and a Peat and Clay unit. Channel unit sands wedge out to the west; less and less of the unit was found as mining uncovered the section in that direction during 1972 and 1973. The Channel unit is overlain by the clay member of the Peat and Clay unit; the peat member lies on top of the clay member and the Current unit. Thus, in trenches V and II, no evidence of the Channel unit exists beneath the peat or above the Current unit. A chance roadcut or river bank exposure of Pleistocene sediments may not show the Channel unit phase of deposition at all; large scale mining operations such as those in the Texasgulf pit are perhaps necessary to unravel the complexities of the Pleistocene section of North Carolina.

No known biogenic structures were found in the Channel unit, with the possible exception of one or two small V-shaped "kinks" ("sitz marks"?) in heavy mineral layers of trough cross-beds. For this reason, and because the overlying Peat and Clay unit apparently is freshwater in origin (p. 266), we conclude that the Channel unit consists of fluvial fill. Primary physical structures in at least one section suggest a fining-up sequence (Allen, 1965:142); trough cross-beds in coarse to medium sand are dominant near the base (Figure 13), and ripple laminae in medium to fine sand at the top. In other sections, trough cross-beds having minor climbing ripples comprise the entire Channel unit.

The sequence of events that led to deposition of the Channel unit is believed to be (1) erosion (presumably during lowered sea level that accompanied a glacial event) and cutting of the channel down to the depth of the Mud and Sand unit; (2) deposition of cross-bedded sand in a fining-up sequence (presumably as the stream's base level rose with rising sea level); and (3) abandonment of the channel and subsequent filling with sediments of the clay member of the Peat and Clay unit.

We deduce that no marine water, or even a salt wedge of estuarine circulation, entered this channel until after deposition of the peat member of the Peat and Clay unit. For this reason, trough cross-bedded sands bearing *Ophiomorpha* and *Skolithos* found in sections elsewhere (Austin, 1973) must not be correlated with the Channel unit unless they clearly are (1) confined to an elongate channel and (2) overlain by freshwater peaty deposits which, in turn, are (3) overlain by the marine Mottled unit.

A radiocarbon date on wood from the top of the Channel unit in trench III (as of 1971) exceeded 42,000 years BP (Smithsonian Institution, Radiocarbon Laboratory, sample SI-1827). Francis M. Hueber identified the wood as the red cedar, *Juniperus* species aff. *J. silicicola* (Small); the genus is common along the Coastal Plain of North Carolina today. Thus, the channel was situated in a coastal setting.

### Peat and Clay Unit

The Peat and Clay unit ranges in thickness from 6 inches (15 cm) to 11 feet (3.4 m). It consists of two members: (1) the peat member and (2) the clay member. Although these two lithologies intergrade with one another, the clay member generally overlies the Channel unit, the peat member overlies both the Channel unit and the Current unit, and the clay member grades upward into the peat member where the former is present (Figure 4). Both members are found in the west and east wall of the mine.

The clay member, where rich in organic debris, is a light chocolate brown when wet (it loses approximately one-third of its volume when dried) and is brownish gray where less rich in organic debris. It has no apparent internal laminae, although a crude bedding is seen (Figure 15). The only fossils found were burrows and rare plant remains. In one locality (trench III, Locality W-2, Figure 2) the peat apparently had been stripped away, and the clay member is riddled with *Thalassinoides* species down to a depth of 3 feet (1 m). Elsewhere, these burrows, which extend down from the Mottled unit, penetrate both the peat and clay. Burrow density increases upward to the top of the clay member. Each burrow is filled with pure white quartz sand, believed to be related genetically to the overlying marine Mottled unit.

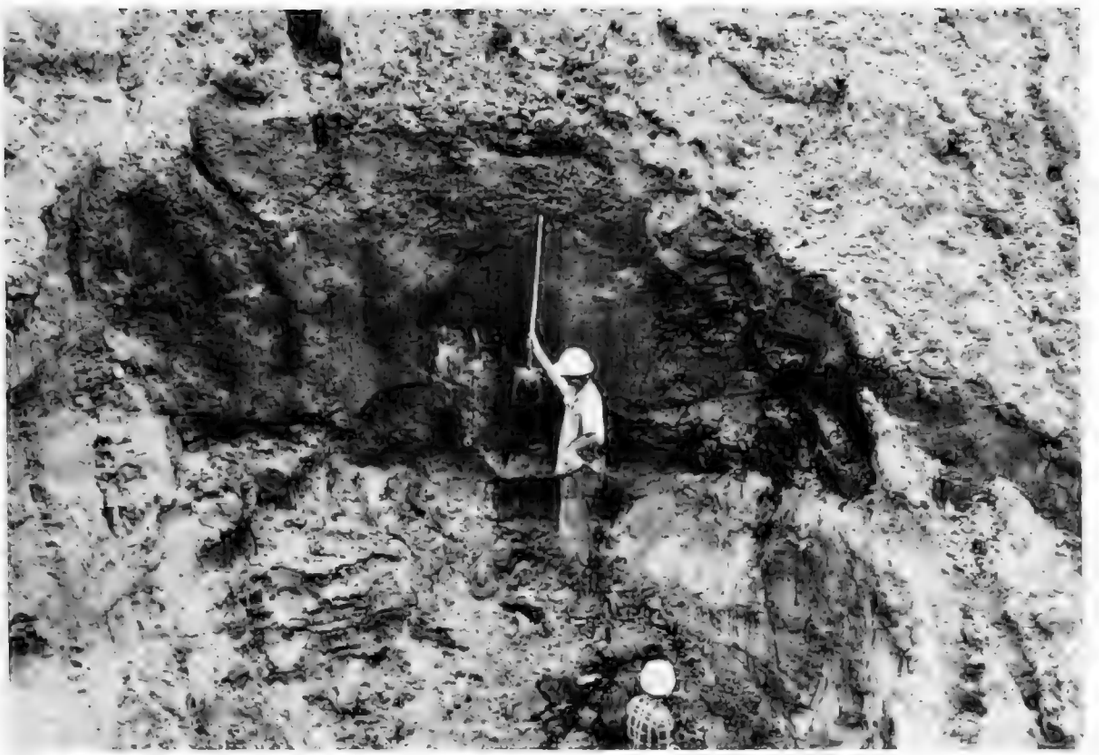

FIGURE 15.—Clay member of Peat and Clay unit. Contact with underlying channel unit is 1 foot (30 cm) below shovel. Abundant *Thalassinoides* sp. filled with sand gives clay a "riddled" appearance (tip of shovel handle to top of exposure, 2 ft; 60 cm). Mottled unit was removed by mining. No peaty sand is preserved at this site. Trench III, near section 2 of Welch (1972).

The peat member is a very granular, sandy, organic deposit containing roots and an occasional limb or twig of a woody plant. Its sandy, rubbly fabric is more like a soil than a true peat, and it may have been partially reworked by the sea during initial deposition of the Mottled unit. Where the clay member of the Peat and Clay unit is not present, the peat member lies stratigraphically between the Current unit and the Mottled unit (Figure 4), although in places the peat member, too, is missing.

We believe that the clay member of the Peat and Clay unit resulted from clay deposition after abandonment of the fluvial channel that previously had filled with sand (Channel unit). At the east end of the mine, only the clay plug and overlying peat were found (Figure 14). Clay plugs are common in fluvial deposits, and also are found in abandoned delta distributary channels. The overlying peat member is a freshwater deposit (based upon pollen analyses; Whitehead, p. 266 herein). Because it is almost completely confined to the region of the Channel unit, it probably represents a local coastal swamp that developed over the old channel and adjacent lowland surface. The entire depositional history, from Channel unit sands through peat development, is one of progressive decrease in (1) sediment grain size, (2) energy of water movement, and ultimately in (3) supply of terrigenous sediment. The peaty deposit represents this last stage. Because the entire sequence can best be explained in terms of a rising sea level (including the marine Mottled unit above the peat), we believe that the freshwater peaty sediment was developed in a coastal region near sea level, similar to much of eastern Georgia and the Carolinas today.

A sample of peat collected in 1971 from the top of the peat member in trench III was dated by the Smithsonian Institution's Radiocarbon Laboratory (sample SI-1829). The date exceeded 42,000 years BP. Thus, the peat member is not a late Wisconsinan interstadial deposit. This date, coupled with Whitehead's assessment of the pollen, suggests a probable Sangamon age. It compares favorably with a Sangamon age derived

from similar pollen from the Bull Creek peat, Horry Co., South Carolina (Whitehead and Campbell, 1976), but less favorably with interstadial pollen (Sirkin, Denny, and Rubin, 1977).

### Mottled Unit

The Mottled unit ranges in thickness from 4 to 9 feet (1.2 to 2.7 m) and occurs throughout the western part of the mine. It was not recognized in the cut at the eastern side of the mine, although all other units below it, excepting the Channel unit, were found. Its apparent absence may be explained by (1) its elimination by a facies change, (2) intense leaching, which destroyed the color contrast so that biogenic structures no longer are visible, or (3) its removal during early stages of mining. Nevertheless, we believe this unit to be widespread, and because it locally overlies a freshwater peat, it is of great significance in environmental interpretation.

The Mottled unit consists of moderately to poorly sorted fine sand mottled with mud. It varies in color from light gray to tan and dark gray, depending on the percentage of mud mottles. The mottling originated through intense bioturbation (Figure 16), which characterizes this unit.

Physical sedimentary structures are found only where bioturbation was less intense; these undisturbed areas occur as small patches only inches (cm) across. The original primary structures seem to have been interlayered sand and mud, in about equal proportions. Some suggestion of mud-draped ripples was found. The deposition rate was slow, however, and because of the active infauna, the sediments were intensely churned. The Mottled unit generally is fine to very fine sand, moderately well to poorly sorted (Figure 8); sample means range from 2.2 to 3.16 $\phi$ and standard deviations from 0.75 to 1.49 $\phi$. The Mottled unit and sandy member of the Mud and Sand unit have similar textural characteristics (Figure 5).

The biogenic structures recognized include *Ophiomorpha nodosa*, *Skolithos linearis*, and *Planolites beverleyensis*. Other traces include two types of crab burrows and various escape structures, the latter possibly by anemones, although some of the more irregular ones possibly are bivalve resting traces. No fossil shells were found, but molds of several genera occur where concretions formed around one type of crab burrow. The other type of crab burrow is related to the top of the Mottled unit, perhaps developed high intertidally or supratidally (they are similar to *Ocypode* or perhaps *Cardisoma* burrows; Shinn, 1968, pl. 111: fig. 1; Frey and Mayou, 1971), and thus may not have been genetically involved with the marine Mottled unit. The concretionary burrows are found within the Mottled Unit. These became hardened with limonite that developed as a crust over a clay and sand wall (Figure 17) possibly formed by the stone crab *Menippe mercenaria* (Curran and Frey, 1977:158). The shells were in the Mottled unit and incorporated in the wall of the burrow.

Shells identified are the gastropods *Oliva* and *Terebra* and the bivalves *Tellina*, *Mulinia*, *Ensis*, and a scallop. *Mulinia* occurs in great numbers. Most shells are broken. No other trace of shell material was found in the normal mud and sand lithology of the Mottled unit. Waters and bottom sediments during deposition of the Mottled unit must have been rich in organic nutrients to support so many suspension and deposit feeders; and perhaps the organic matter formed acids that later dissolved most shells away. Such sediments today typically are highly reduced, having low pH; except for the crab-burrow concretions, no evidence would remain of marine shells once present in abundance. This led us to wonder whether local conditions within other marine units of the Pleistocene section in the pit might not preserve some shells; but they remained elusive, perhaps having been dissolved away without a trace (cf. Stephens, Eason, and Pedlow, 1973; Frey, 1975, fig. 2.2).

Crab burrows that developed concretions easily could be reconstructed as branched and unbranched, downward trending tunnels. Other crab burrows, however, did not develop concretions. The latter are 2 inches (5 cm) in diameter, penetrate more than 1 foot (30 cm) into the substrate, and are filled with clean quartz sand,

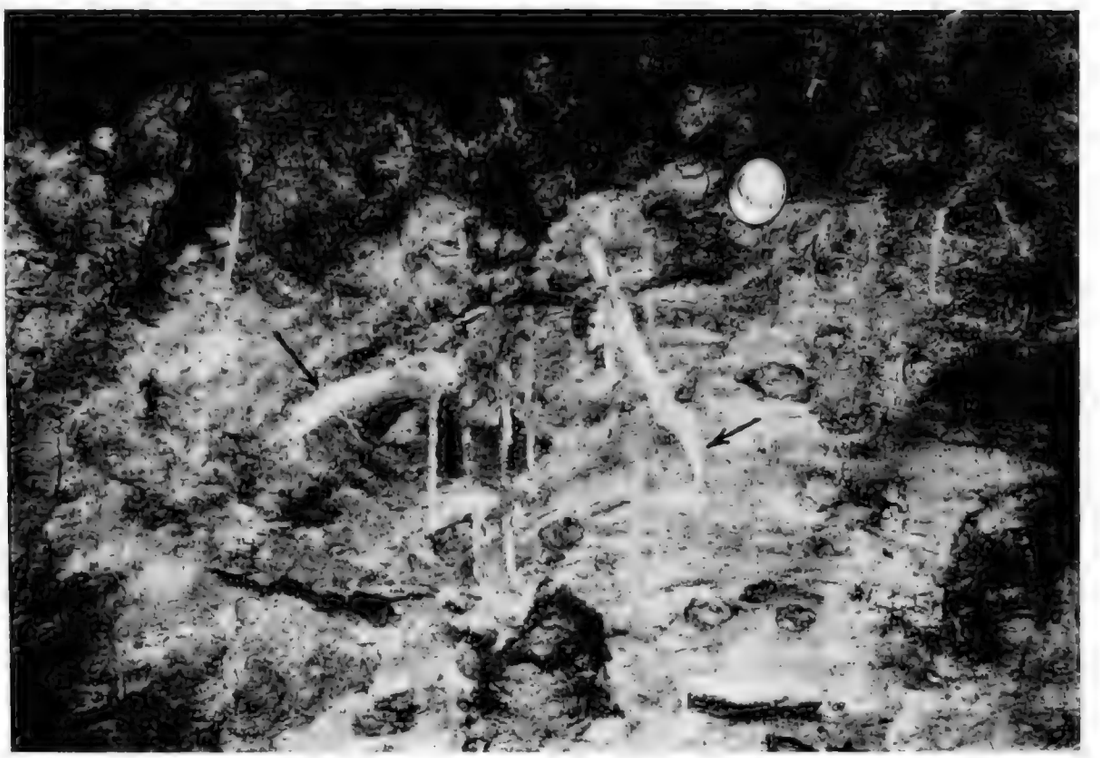

FIGURE 16.—Mottled unit. Bioturbation largely destroyed original physical structures. Vertical tubes (white) are *Skolithos linearis*; dark clay rings are *Ophiomorpha nodosa*; large white diagonal burrows having very thin wall (arrows) possibly are *Planolites* or *Palaeophycus*. Trench V, southwest side, 1971.

FIGURE 17.—Crab burrow exhibiting *Tellina* sp. mold in limonite crust, Mottled unit. Pits on surface of burrow (here merely a segment of a much larger structure, the upper part being entirely unlithified) are molds of broken bits of other shells, many of which are *Mulinia* sp. Trench III, northwest corner, 1971.

evidently derived from the overlying Rooty unit. These J-shaped burrows possibly were made by the ghost crab *Ocypode quadrata* (Curran and Frey, 1977:159).

Uniform mottling and general textures of the Mottled unit persist throughout the region studied in the west end of the pit, whereas other muddy sand units show extreme variability even within the 0.65 mile (1.2 km) north-south exposure. Therefore, the Mottled unit must have had a more uniform environment of deposition; sediments might have been deposited in a lagoon or estuary of nearly normal salinity. A shallow subtidal to intertidal flat, landward of a bay-mouth barrier or in the lower reaches of an estuary (as in Georgia today; Howard and Frey, 1975, 1980c), seems probable. Bioturbation by diverse organisms is intense at such sites, and most physical sedimentary structures are modified or obliterated; the result is a mixture of highly bioturbated muddy sand or sandy mud. We see no evidence for a protective barrier to the east, although such evidence might be forthcoming in further studies. However, tidal flats also may form in estuary mouths adjacent to the oceanward side of barriers where energy levels are reduced, as on protected parts of the Georgia coast (Howard and Dörjes, 1972). Shallow subtidal mud and sand facies are found immediately offshore of Sapelo Island (Howard and Reineck, 1972:93, 100). The geometry of the unit may be crucial in determining which of the depositional models is most appropriate.

After deposition ceased, intertidal to supratidal crab burrows (*Ocypode*, or possibly *Cardisoma*) evidently were excavated in the unit, either from the overlying Rooty unit (which was not then rooty) or during the time between deposition of sediments of the Mottled unit and Rooty unit (if the latter is a terrestrial deposit). These conclusions further suggest retreat of the sea following deposition of the Mottled unit. This possibility is not easily documented because (1) the contact between the Mottled unit and overlying Rooty unit is obscured by root mottling and may be gradational, and (2) we are not sure of the depositional environment of the Rooty unit.

### Rooty Unit

The Rooty unit, the uppermost unit in the section, consists of yellow to tan and rusty orange, fine- to medium-grained sand and ranges in thickness from 3 to 6 feet (1 to 1.8 m). The lower contact in most places is gradational with the underlying Mottled unit, but locally it is a sharp surface. Older Holocene and modern roots have penetrated this unit; a swamp overlying it prior to opening of the mine leached sediments considerably. These sediments apparently either lacked primary physical structures or, if present, were destroyed by ubiquitous subvertical root structures and leaching. Limonitic concretions are common around rootlets. Two sediment samples from the unit show it to be medium- to fine-grained (1.31 to 2.68 $\phi$), moderately well-sorted (.50 to .59 $\phi$), quartz sand. Small amounts of clay were seen at other localities.

Thus, for environmental interpretation, we have only stratigraphic position, grain size, and sorting which, at best is poor evidence considering the severe disturbances by subsequent roots and leaching (cf. Scott, 1976). We therefore refrain from speculating on the origin of this unit beyond the possibility that it might represent a high intertidal to supratidal sand deposit occupied by crabs (Curran and Frey, 1977:158–159).

## Cycles of Sedimentation

In the foregoing account, we noted five erosional surfaces above the Yorktown (the fifth is the present land surface) and discussed units between them. We believe that these depositional units combine to form discrete cycles of sedimentation, as outlined in Table 1. Additional data not incorporated in the table, but supportive of the interpretation presented and discussed in the text, include (1) *Corbicula densata* in Shell Hash unit, which suggests brackish water conditions at level of erosional surface B; (2) tree stumps in-situ at top of Mud and Sand unit, which suggest freshwater or terrestrial conditions and marine regression at horizon of erosional surface C; and (3) high intertidal to supratidal crab burrows at

top of Mottled unit; these burrows are related genetically to Rooty unit and suggest marine regression at that level.

It often is difficult to separate depositional responses that produce cycles. Processes or conditions that control sediment influx may be related to stillstands of sea level or sea-level changes, whether of eustacy or tectonism. Classical American cyclothems were long considered to result from sea-level changes (Moore, 1930, 1964:287, 368, 369; Weller, 1930:115–132, 1964:614–618), sedimentational effects playing a minor role (Belt, 1975:427–430). With detailed information about various types of modern deltas around the world, especially the Mississippi, cyclothems are typically considered the result of delta-lobe switching or comparable sediment-related processes, sea-level changes playing a minor role. Nevertheless, the complex interplay of sediment influx, eustacy, tectonism, compaction, and marine effects (tidal range, wave and current intensity) are perhaps too difficult to sort out (Oertel and Walton, 1967); generalizations about cyclic deposits may be misleading, although recently there has been some progress (Belt, in press).

Obvious eustatic changes occurred during the Pleistocene, and because the Peat and Clay unit is most likely Sangamon, we can relate cycle IV (Table 1) to an estuarine cycle of deposition, accompanying an interglacial rising sea much like that of the early Holocene (Kraft et al., 1979). Furthermore, recent evidence (Minard et al., 1974; Belknap and Kraft, 1977) suggests that the continental shelf of the Atlantic Bight, especially the Baltimore Canyon trough, presently is sinking actively, but that this sinking is (and has been during the Holocene) much less in the North Carolina area. Complexity of stratigraphic relationships (Figure 4), especially later cycles nested into earlier ones, also suggests that little tectonic subsidence occurred in this region during the Pleistocene. Even with moderate subsidence, each cycle would have been more nearly complete, having obvious transgressive phases. One also would see less lenticularity in maximum salinity (maximum rise of the sea?) phases, although abrupt lateral and vertical facies changes are typical of estuarine sequences (Howard and Frey, 1980b). Thus, in our interpretation of cycles, we made the assumption that tectonic instability was minimal, albeit probably somewhat greater than in adjacent South Carolina (Winker and Howard, 1977, figs. 1, 2).

The other important parameter, amount of sediment influx, is more difficult to determine: whether the Pleistocene coast of North Carolina (1) was a strike-fed barrier island coastal system, perhaps related to small-scale delta progradation on the continental shelf (such as the sea island coast of South Carolina and Georgia), or (2) consisted of deeply drowned river mouths, open-water lagoons, and barrier islands (such as present North Carolina and the Atlantic Bight). These two end members would result in coastal successions of moderate to high, or moderate to low sediment influx, respectively.

Erosional surfaces observed in the mine (Figure 4) were probably the result of eustatic changes accompanying growth and decay of continental ice sheets. Within each cycle, a change in relative sea level is recorded: either a lowering of sea level, or aggradation of sediment to sea level, in the uppermost layers. Of the cycles, only cycle IV records a gradual transgression of the sea; in other cycles, maximum salinity (whether marine or brackish) apparently is represented by strata directly over the surface of erosion (Table 1). The Shell Hash unit possibly is a transgressive deposit, a "destructional" unit above the Upper Shell unit. The progression from the Channel unit, through the Peat and Clay unit, to the Mottled unit evidently is an example of facies onlap; the Channel unit through Peat and Clay unit is the transgressive phase, the Mottled unit represents maximum sea-level rise, and possible high intertidal to supratidal crab burrows at the top indicate either a lowering of sea level or accretion of sediment to sea level, although the latter is less likely because of thinness of the Mottled unit.

Almost all data published on the Holocene transgression in the Delaware Bay–southern New Jersey–Delmarva Peninsula area (Kraft, Biggs, and Halsey, 1973; Kraft et al., 1979, and references cited therein) show successions that com-

monly include salt marsh peat or peaty sediment at the base (above the Wisconsinan unconformity) overlain by lagoonal muds and then barrier-offshore sands, near or at the top. The basal peat could result only where a barrier island or estuary mouth existed farther seaward.

Cycles of the Delaware coast show thick transgressive phases of three types (Kraft, Biggs, and Halsey, 1973; Sheridan, Dill, and Kraft, 1974): (1) salt marsh peat overlain by lagoon muds and sand, overlain by barrier island or offshore marine sands; (2) estuarine or lagoonal muds and clays overlain by nearshore marine sands; or (3) salt marsh peat overlain by estuarine muds overlain, in turn, by modern salt marsh peat. Type 1 evidently resulted from deposition behind a bar-

TABLE 1.—Stratigraphic units, depositional environments, and cycles of sedimentation, Lee Creek Mine, North Carolina (except for Yorktown, all units are informal; asterisks indicate inferred

| *Surface and unit* | *Environmental interpretation* | *Cycle (Age)* |
|---|---|---|
| PRESENT LAND SURFACE | | |
| Rooty | *High intertidal* to *supratidal* (beach backshore or dunes; Curran and Frey, 1977) or *terrestrial environment*; now obscured by intense root mottling and leaching of sediments. | IV?, V? (early Holocene?; latest Pleistocene?) |
| POSSIBLE EROSIONAL SURFACE | | |
| Mottled | *Normal or nearly normal marine salinity in relatively low-energy, *shallow subtidal* to *intertidal flat environment*, either in seaward reaches of an *estuary* or *lagoon*, or estuary mouth along or adjacent to a protected beach (cf. Howard and Dörjes, 1972); inhabited by relatively diverse animals, some of which burrowed into sediments of underlying unit. | IV (Sangamon?) |
| Peat and Clay | *Freshwater deposits* accumulating first as local clay plugs in *abandoned fluvial channels* (*clay member*), then as fresh water *coastal swamp* peaty sands spread over local low areas (*peat member*); peaty sands partly reworked locally during subsequent marine inundation, and clays burrowed by marine organisms. | IV (Sangamon) |
| Channel | Strictly nonmarine, *fluvial channel* along coastal lowland, incised into underlying sands during marine regression; channel remnants later filled with clays of overlying unit. | IV (Sangamon) |
| EROSIONAL SURFACE D | | |
| Current | Normal or nearly normal salinity in *shallow subtidal* to *intertidal* (point bar or tidal shoal) *environment* in low reaches of *ebb-dominated estuary* inhabited by diverse burrowing animals; energy levels slightly higher, and mud and lebensspuren content of sediments lower, during early deposition (*tabular cross-bed member*) than during later dep- | III (middle Pleistocene?) |

rier island; type 2 is off Bethany Beach on the Atlantic inner shelf; and type 3 developed within the mouth of the Delaware estuary, where no offshore barrier was necessary to protect the basal peat. In the model of Sanders and Kumar (1975), applied to the south shore of Long Island, the breaker zone (and hence the barrier island) "jumped" 3 miles (5 km) to the north (landward) to form a new set of barrier islands and lagoons that evolved to the present coastline. Thus, only progradational phases would be well developed; transgressive phases of cycles most likely would be absent or very abbreviated, although in the Field and Duane (1976) model no "jumps" are postulated. The areas studied by Kraft and others can be classed as the coastline end-member of

maximum salinity during major stillstand of sea; italics indicate type of environment; for additional data, supportive of the interpretations presented here, see "Cycles of Sedimentation," p. 252)

| *Surface and unit* | *Environmental interpretation* | *Cycle (Age)* |
|---|---|---|
| | osition (*wavy bedded member*). Initial transgression produced "starved" basal conglomerate of erratic rock clasts on top of underlying unit. | |
| EROSIONAL SURFACE C | | |
| Mud and Sand | Nearly normal to slightly brackish salinity in *shallow subtidal* to *intertidal*, low-energy environment in middle to lower reaches of *muddy estuary* inhabited mainly by burrowing animals (*mud member*), cut-and-filled locally by higher energy *channel scour*, perhaps partially aggraded by *point bar deposits*, in waters of nearly normal salinity and low animal diversity (*sand member*). Emergent top of unit eroded during subsequent marine regression and (or) aggradation of sediments to sea level. | II (early Pleistocene?) |
| Shell Hash | *Normal or nearly normal salinity in *estuarine channels or estuarine inlet-shoal system* of high energy levels and low animal diversity, a "basal conglomerate" of shell hash reworked from underlying unit during initial marine transgression. | II (early Pleistocene?) |
| EROSIONAL SURFACE B | | |
| Upper Shell | *(1) Normal to nearly normal in *moderately shallow, nearshore shelf* or *open estuary* waters inhabited by diverse mollusks, during early deposition, followed by (2) decreased salinity, water depth, and molluscan diversity in *shallow subtidal* to *intertidal* environment in middle reaches of estuary, then (3) erosional cut-and-fill by *estuarine channels* or migrating *estuary-inlet scour holes* (cf. Howard and Frey, 1980b, 1980c) during marine regression. | I (earliest Pleistocene?; latest Pliocene?) |
| EROSIONAL SURFACE A | | |
| Yorktown Formation ("Boulder bed") | Normal salinity in *shallow, nearshore-shelf* waters of moderately low energy levels and high animal diversity; upper 10 ft (3m) of unit. | (Pliocene) |

low sediment influx, mentioned above.

More complex sections are found in the sea island coast of Georgia and South Carolina (Colquhoun, Bond, and Chappel, 1972; Henry, Giles, and Woolsey, 1973). These sequences apparently lack a lower peat layer during transgression. Peat also is absent in sections of eastern North Carolina that record Holocene transgression, although soil is developed (Pierce and Colquhoun, 1970a, 1970b). In South Carolina and Georgia, vertical sequences recording the history of sea-level fluctuation, transgression, and progradation are not well documented, but clearly they are more complex than previously thought (Colquhoun et al., 1980; DePratter and Howard, 1977, 1980, 1981). The known stratigraphic record is a complicated series of highly asymmetric cycles replete with abrupt lateral and vertical facies changes and erosional surfaces. Reworking of older beach or offshore deposits by subsequent estuarine processes can destroy all traces of the transgressive phase, whether or not a major unconformity is involved (Howard and Frey, 1980b; Wojtal and Moslow, 1980). Sections described previously from the late Pleistocene and Holocene of North Carolina (Pierce and Colquhoun, 1970a, 1970b) are too ambiguous in specific details for resolving progradational or transgressive phases of cycles.

Our data clearly show that, except for cycle IV, all cycles contain only a slight (cycle II) or no visible transgressive phase (cycles I, III). As stressed previously, maximum relative salinity evidently occurred near or at the base of the lower three cycles (Table 1). We interpret these salinity maxima as maximum stillstands of the sea (regardless of absolute magnitudes of sea-level changes) as represented by the preserved record. If active tectonic subsidence occurred during or just prior to the time of stillstand, a thick transgressive phase presumably would have been deposited beneath the maximum salinity unit. The thin or nonexistent transgressive phase of cycles I, II, and III is consistent with a rapid rise of sea level prior to the stillstand. With active sedimentation but a stable tectonic *milieu*, progradation would occur during the stillstand and less than normal salinity would be recorded (as is the case) at the top of each cycle.

Thicknesses of these progradational deposits may have been reduced by erosion following each cycle. The most noticeable example of this is where the Current unit is completely cut out by the Channel unit in several exposures. There ought to be other cases of reduction in thickness wherever we indicate erosion surfaces. These would show up outside our study sections. Only in the Mud and Sand unit is a thick progradational phase preserved within a cycle; this interpretation is consistent with the presence of upright tree stumps, which strongly suggests that erosional downcutting between cycles II and III was not very deep.

Cycle IV, the major exception, has a well-developed transgressive phase, beginning with the Channel unit and culminating in the Mottled unit, and even includes a transgressive freshwater peat unit. Because this is a Sangamon cycle, just prior to Wisconsinan glaciation, it was not involved in possible early Holocene deltas developed at the present site of Hatteras and Lookout shoals (Hoyt and Henry, 1971). The marine-related phase (Mottled unit) is abbreviated in cycle IV, whereas in earlier cycles it is better developed. Perhaps the mean coastline (average coastal position during transgression and regression) had prograded farther east by the time of cycle IV deposition than during earlier cycles. Perhaps the coastal region also was more emergent following earlier cycles, reflecting a tectonic influence. Cycle I is much thicker and more nearly marine than the Mottled unit of cycle IV; cycles II and III also are marine influenced, but are more restricted than cycle I.

Overall, the Lee Creek section (Figures 3, 4, Table 1) bears considerable resemblance to a progradational estuarine sequence, despite the number of cycles and erosional surfaces involved. In idealized estuarine models for the Holocene of the Georgia coast (Howard and Frey, 1980b, 1980c) and to some extent on Kiawah Island, South Carolina (Wojtal and Moslow, 1980), the sequence begins with bedrock (Pleistocene or Tertiary) under an erosional surface overlain, in as-

cending order, by (1) channel-lag cross-beds containing many clasts and reworked shells—?Shell Hash unit; (2) channel-fill or estuarine accretionary beds, dominated by bioturbated muddy sands and various combinations of laminated, wavy, flaser, and lenticular bedding, depending on local conditions—?Mud and Sand unit; (3) point bar, tidal flat, and shoal deposits, dominated by ripple-laminated to cross-bedded point bar or shoal sands—?Current unit; and (4) channel-bank and salt marsh muds. The Upper Shell unit perhaps represents a condensed version of phases 1, 2, and 3. Units of cycle IV are obvious exceptions, as mentioned previously.

If our environmental interpretations are correct, the possibility remains that erosional surface C may represent a diastem or lesser hiatus, rather than a major unconformity, in an overall estuarine sequence beginning with the Shell Hash unit and culminating in the Current unit. However, in situ tree stumps at the top of the Mud and Sand unit and the "conglomerate" along the erosional surface (Table 1) suggest a depositional break of considerable magnitude. Thus, as preserved, not only are the cycles asymmetrical, but respective hemicycles also are markedly incomplete.

Temporal and environmental placement of the Rooty unit (Table 1) remains problematical. Elevation and stratigraphic position of the unit suggest that it may be analogous, genetically, to dune-like and backshore deposits capping a Pleistocene shoreface-foreshore sequence along St. Marys River, Florida (Frey and Mayou, 1971; Scott, 1976). Crab burrows "piping" Rooty unit sands into the top of the Mottled unit also support this interpretation (Curran and Frey, 1977). Such reasoning is our main basis for considering the Mottled unit to represent an estuary-mouth, beach-related tidal flat (Howard and Dörjes, 1972) rather than a fully estuarine environment; physical and biogenic sedimentary structures are similar in both places (Howard and Frey, 1980c), except for crab burrows in adjacent high intertidal or supratidal beach- or dune-like sands.

Our postulated estuarine progradational coast ("sea island" style) is difficult to relate, lithostratigraphically, to the Suffolk (Pamlico) Scarp 5.7 miles (9 km) west of the Lee Creek Mine. Pleistocene stratigraphy west of the north-northwest trending scarp appears to be almost entirely different from that east of the scarp (Daniels et al., 1972; Austin, 1973), and from that south of the Cape Fear River (Winker and Howard, 1977; DuBar and DuBar, 1980). The basic model of a primary barrier lacking an open lagoon (Coch and Krinsley, 1971; Colquhoun, Bond, and Chappel, 1972; Colquhoun, 1974) best fits our observations, although Otvos (1972) considered the Suffolk ridge to be a barrier beach system having an open lagoon to the west. Oaks and Coch (1973:25) and Oaks et al. (1974) considered the structure to be an erosional feature, either by high energy of the open sea or by lagoon-shore erosion of headlands, or both, which is consistent with presently known evidence from South Carolina (Colquhoun, 1974).

Because of markedly different lithofacies and lack of refined regional biostratigraphic zonations, temporal implications of Lee Creek cycles (Table 1) are difficult to fit into regional patterns of emergence or submergence during the late Tertiary and Pleistocene, whether to the south (Winker and Howard, 1977, fig. 3, table 1; DuBar and DuBar, 1980, table 1) or to the north (Oaks and Coch, 1973, table 6). Long-distance correlation of individual formations is virtually impossible, and correlating sequences between erosional surfaces is risky, particularly among estuarine sequences (Howard and Frey, 1980b:230). Other problems of correlation were summarized by Oaks and DuBar (1974).

Cores that penetrated the entire Quaternary sequence in southeastern Virginia (Oaks and Coch, 1973) rarely exceeded 180 feet (60 m) in depth; most were 50 to 75 feet (15 to 23 m) deep. The greater thicknesses were found in channel fills. Our entire section is approximately 30 feet (9 m) thick; the contrast implies greater net subsidence in Virginia. However, our data are from but one section, which may be a preserved remnant of an interfluve; clearly, additional data need to be collected from North Carolina.

Finally, Oaks and Coch (1973, pl. 2) indicated

a prograding coast in the sand ridge and mud flat complex, which developed during Sand Bridge (late Sangamon?) deposition, their upper units. Data for their other formations are difficult to interpret in terms of proportions of progradation and transgression within a cycle, but the maximum depositional phase is well displayed in their paleogeographic maps. Perhaps the style of deposition changed throughout the Pleistocene.

### A Lesson in Stratigraphy

Because of trenches dug for ground water drainage at the west end of the Lee Creek Mine near Aurora, North Carolina, excellent three-dimensional exposures of the post-Yorktown section were continuously being uncovered during our investigation. These ephemeral exposures, studied during the summers of 1971 and 1972, and verified in the summer of 1973, revealed a complex set of facies that fit into four depositional cycles, each separated by an unconformity.

Total cumulative thickness of the units measured is approximately 95 feet (29 m), but the net thickness of the section from the top of the Yorktown to the top of the Rooty unit (present land surface) is merely 30 feet (9 m). The reason for this apparent disparity is that erosional surfaces were cut down and filled over with sediments that do not appear elsewhere (Figures 3, 4), and some units thin from one end of the exposure to the other. This internesting of cycles indicates that tectonic subsidence was not rapid during the Pleistocene; during each lowering of sea level, erosion removed much of what had been deposited during the earlier cycle.

Recognition of erosional surfaces that separate the four cycles depended substantially on three-dimensional stratigraphic control. We could "walk out" contacts (in many directions) and prove their correlation. Once this framework was established, internal consistency of facies became apparent. The situation points up the uniqueness of broad, many faceted exposures such as those in the Lee Creek Mine, and the inadequacies of "normal" Pleistocene exposures elsewhere in the Coastal Plain of North Carolina. If, for example, a roadcut or river bank showed only the exposure as seen in trench V, the entire Channel unit and clay member of the Peat and Clay unit would have been missed. The peat would have been considered a natural capping to cycle III, above the intertidal wavy bedded member of the Current unit, whether fresh water (in this case) or salt marsh (in a completely preserved estuarine sequence); the contact appears to be conformable. Most outcrops elsewhere provide only parts of the total sequence. Only with difficulty, for example, could one correlate with our Lee Creek sequence another sequence that showed a shell bed overlain by a sandy bioturbated mud, overlain in turn by structureless, fine-grained quartz sand (such an exposure occurs along the Pamlico River; Austin, 1973:46–60). In fact, we cannot know whether we have accounted for all cycles actually represented at the site of our section. Perhaps additional exposures created by mining will reveal other units at different unconformity levels. For this reason, we cannot "count back" and assume that the Mud and Sand unit is Aftonian, for example, or that all coastal sections should contain exactly four cycles within the late Tertiary-Pleistocene sequence.

In short, the amount of detail that we were able to obtain from the section, including burrow structures and knowledge of their modern analogs, is perhaps a bare minimum for understanding the complex facies and relative time events represented. Any less information would be inadequate for determining the position of erosional surfaces and the continuity of cycles between them. Perhaps more details on Pleistocene physical and biogenic structures (including X-ray radiographs and sediment peels) will provide significant additional information. More refined correlations with the mine section and elsewhere might yet be possible. Incomplete or inadequate sections (few go down to the Yorktown, and even fewer provide three-dimensional stratigraphic control), leaching of shells and soluble heavy minerals, and destruction of primary physical and biogenic structures by modern roots will remain a problem. In the meantime, we urge a

very conservative approach to lithostratigraphic nomenclature (hence our informal unit names); experience here and elsewhere on the Coastal Plain shows that problems frequently arise in the formal naming of new, or indiscriminate redefinition of old, stratigraphic units. Because of complex facies changes, many named formations cannot be traced with certainty outside their type areas.

Nevertheless, because of more detailed data than is usual in Coastal Plain studies, we were able to demonstrate a progradational, estuary-related coastal zone during development of cycles I, II, and III, and an overall eastward shift of the shoreline during cycle IV. The principles developed here may be of use in distinguishing progradational and transgressive cycles in other Pleistocene sections.

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# Pollen Analysis of the Peat Member from the Lee Creek Mine

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ABSTRACT

A pollen analytical study of the peat horizon exposed in the Lee Creek phosphate mine indicates that it was deposited in a freshwater environment during interglacial time (probably Sangamon). The freshwater nature of the deposit is suggested by the high percentage of sedge and grass pollen; the presence of *Potamogeton*, *Brasenia*, *Nuphar*, *Myriophyllum scabratum*, *M. heterophyllum*, *Pontederia*, *Sagittaria*, *Nymphaea*, *Typha-Sparganium*, and *Isoëtes*; the occurrence of *Botryococcus*, *Pediastrum boryanum*, and *Tetraedron*; the low percentage of chenopod-amaranth pollen; and the absence of brackish indicators, such as *Ruppia* and *Iva*. The interglacial age (rather than interstadial) is suggested by the general absence of "boreal indicators," the similarity of the tree pollen frequencies to those from interglacial deposits both to the north and south, and the general similarity of the fossil spectrum to modern pollen assemblages from eastern North Carolina.

## Introduction

Stratigraphic work on the sections exposed in the Lee Creek phosphate mine (Belt, Frey, and Welch, herein) has indicated the probable existence of at least four depositional sequences of Pleistocene age. The uppermost cycle (cycle IV) consists of fluvial channel materials, which cut into deposits of both cycles III and II, a clay member (apparently deposited in the abandoned river channel), a peat member (discussed in the present paper), and a marine unit overlying the peat. The radiocarbon age of the peat is >42,000 BP (SI-1829).

Given the sequence of sediments associated with this depositional cycle, it would be of interest to determine whether the peat represents a freshwater deposit (a freshwater marsh deposit associated, at least initially, with the abandoned river channel) or whether it was formed in a brackish environment (related to the continuing transgression that produced the overlying marine sediments). Given the infinite radiocarbon date, it would also be of interest to determine whether this depositional unit dates from the Sangamon or from a mid-Wisconsinan interstadial. With these general questions in mind, I undertook a pollen analytical investigation of the peat.

## Methods

Four samples of the peat and/or clay were analyzed. Two samples derived from trench III, one from trench IV, and one from the east wall (Figure 2 of Belt, Frey and Welch, herein). The samples were prepared by a standard procedure (boiling in KOH, demineralizing with HCl, boiling in conc. HF, and acetolysis) and mounted in silicone oil. Counting was carried out at a magnification of 400 diameters using a Leitz Orthoplan microscope with apochromatic objectives.

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## Results

The samples from trenches III and IV contained too little pollen for detailed analysis. The slides consisted of finely comminuted organic debris, mostly too fine and badly preserved to identify. Only five or six pollen grains were present on each of the slides and they were often badly corroded.

The peat sample from the east wall differed in that the organic fragments were larger (mostly vascular tissue and leaf cuticular remains) and pollen was both more abundant and better preserved. Three entire slides were counted to obtain sufficient pollen for reasonable interpretations. The results are presented in Tables 1 and 2. Note that two sets of percentages are given. "Percent of total pollen" involves a pollen sum including all tree, shrub and herb pollen, but excluding obvious aquatics. "Percent of arboreal pollen" are percentages for three types based on a pollen sum including only arboreal pollen (AP). The latter calculation was necessary so that the spectrum could be compared more directly with other fossil and modern spectra from the southeast (few published modern and fossil spectra have such high percentages of non-arboreal pollen).

## Interpretations

The high percentages of non-arboreal pollen (NAP) (mostly grass and sedge), and the pollen of a number of different aquatic plants suggest that much of the pollen was locally derived and that the depositional environment was characterized by standing water for at least a portion of the year. This is further substantiated by the presence of fossil algae (*Botryococcus*, *Pediastrum boryanum*, and *Tetraedron*). A number of the aquatics represented occur in a wide range of coastal plain environments, sometimes including brackish waters (these include *Typha*, *Potamogeton*, *Sagittaria*, and *Nuphar*). However, others apparently occur only in freshwater habitats (both species of *Myriophyllum*, *Brasenia*, *Nymphaea*, *Pontederia*, and *Isoëtes*) (Radford, Ahles, and Bell 1964). Furthermore, the algae mentioned above are characteristic freshwater taxa (Smith, 1950:243, 269, 404).

TABLE 1.—Arboreal, shrub, and herb pollen data from the Peat Member, Lee Creek Mine

| Type of pollen | No. of grains | % of total (arboreal) pollen |
|---|---|---|
| ARBOREAL POLLEN | | |
| *Pinus* | 147 | 16.44 (54.85) |
| *Picea* | 6 | 0.67 (2.24) |
| *Abies* | 1 | 0.11 (0.37) |
| Cupressaceae | 21 | 2.35 (7.84) |
| *Quercus* | 60 | 6.71 (22.39) |
| *Carya* | 5 | 0.56 (1.87) |
| *Betula* | 8 | 0.89 (2.99) |
| *Fraxinus* | 3 | 0.34 (1.12) |
| *Corylus* | 5 | 0.56 (1.87) |
| *Nyssa* | 4 | 0.45 (1.49) |
| *Liquidambar* | 2 | 0.22 (0.75) |
| *Ostrya - Carpinus* | 2 | 0.22 (0.75) |
| *Castanea* | 3 | 0.34 (1.12) |
| *Populus* | 1 | 0.11 (0.37) |
| Subtotal | 268 | 29.98 |
| SHRUB POLLEN | | |
| *Alnus* | 140 | 15.66 |
| *Lonicera* | 1 | 0.11 |
| Ericaceae | 5 | 0.56 |
| *Viburnum* | 1 | 0.11 |
| Subtotal | 147 | 16.44 |
| HERB POLLEN | | |
| Gramineae | 215 | 24.05 |
| Cyperaceae | 197 | 22.04 |
| Compositae | 35 | 3.91 |
| Liguliflorae | 2 | 0.22 |
| *Ambrosia* | 5 | 0.56 |
| *Artemisia* | 1 | 0.11 |
| Rosaceae | 1 | 0.11 |
| *Ranunculus* | 1 | 0.11 |
| *Thalictrum* | 5 | 0.56 |
| Umbelliferae | 5 | 0.56 |
| *Sanguisorba canadensis* | 1 | 0.11 |
| chenopod-amaranth | 11 | 1.23 |
| Subtotal | 479 | 53.58 |
| Total | 894 | |

Thus, microfossil evidence is consistent with peat deposition in a freshwater rather than brackish environment. Furthermore, in brackish water sediments I would expect far higher percentages of chenopod-amaranth type pollen, low percentages of sedge pollen, pollen of typical saltmarsh shrubs (such as *Iva frutescens*), and pollen of *Ruppia*

TABLE 2.—Aquatic, algal, and miscellaneous pollen data from the Peat Member, Lee Creek Mine

| Type of pollen | No. of grains | % of total pollen |
|---|---|---|
| AQUATICS | | |
| *Polygonum* (*Persicaria* type) | 2 | 0.22 |
| *Potamogeton* | 2 | 0.22 |
| *Brasenia* | 6 | 0.67 |
| *Nuphar* | 3 | 0.34 |
| *Myriophyllum scabratum* | 3 | 0.34 |
| *Myriophyllum heterophyllum* | 1 | 0.11 |
| *Pontederia* | 2 | 0.22 |
| *Isoëtes* | 3 | 0.34 |
| *Sagittaria* | 6 | 0.67 |
| *Nymphaea* | 1 | 0.11 |
| *Typha-Sparganium* type | 5 | 0.56 |
| ALGAE | | |
| *Botryococcus* | 27 | 3.02 |
| *Pediastrum boryanum* | 2 | 0.22 |
| *Tetraedron* | 1 | 0.11 |
| MISCELLANEOUS | | |
| *Sphagnum* | 11 | 1.23 |
| *Botrychium* cf. *dissectum* | 1 | 0.11 |
| *Osmunda regalis* | 2 | 0.22 |
| Monolete fern | 62 | 6.94 |
| Trilete fern | 1 | 0.11 |
| Unknown | 15 | 1.68 |
| Unidentifiable | 51 | 5.70 |

(e.g., Butler, 1959; Heusser, 1963). Consequently it is quite reasonable to assume that the peat is of freshwater origin.

Much of the herb and shrub pollen (composites, *Thalictrum*, *Sanguisorba canadensis*, alder) probably derived from wet shores immediately surrounding the marsh habitat itself.

The question of the age relationship of the peat deposit can also be resolved, but not quite as definitively. The virtual absence of pollen of "boreal" taxa certainly suggests a temperate environment. Of the many such taxa known from full-glacial and late-glacial deposits in the southeast (e.g., Whitehead, 1963, 1964, 1965, 1967, 1973, 1981; Frey, 1951, 1953, 1955; Craig 1969; Watts 1970), only *Picea*, *Abies* (a single grain), and *Sanguisorba* (a single grain) are represented in the peat. If one ignores the spruce (0.67% total pollen, 2.24% AP), then the spectrum is remarkably like modern pollen assemblages from both northeastern and southeastern North Carolina (e.g., Whitehead, 1967, 1981; Whitehead and Tan, 1969; Frey 1951, 1953). The dominant tree types are pine and oak with a number of other temperate deciduous and coniferous taxa represented. The overall impression is of a vegetation reasonably comparable to the present, with climate perhaps a trifle cooler.

It is thus apparent that the peat was deposited either during an interglacial or during a rather warm interstadial such as the Mid-Wisconsinan Plum Point or Port Talbot (Whitehead, 1973: 630; Dreimanis, 1973:377). The obvious approach is to compare the pollen spectrum from the peat with known interglacial and interstadial spectra from the same general area. Mid-Wisconsinan interstadial spectra are known from the Bay Lakes of Bladen County, southeastern North Carolina (Frey, 1951, 1953, 1955; Whitehead, 1965, 1967), from Rockyhock Bay in Chowan County, northeastern North Carolina (Whitehead, 1973, 1981), and from an exposure along the intracoastal waterway near Long Beach in southeastern North Carolina (Whitehead and Doyle, 1969). Interglacial spectra are known from the exposure at Flanner Beach on the Neuse River (only 50 km from the Lee Creek site) (Whitehead and Davis, 1969) and from the Kempsville formation in southeastern Virginia (Whitehead, unpublished data; Oaks and Coch, 1973). Basically, the spectrum from the peat horizon is more similar to the interglacial spectra. The interstadial spectra differ consistently in having higher percentages of spruce and more frequent occurrence of boreal taxa, such as *Sanguisorba canadensis*, *Arceuthobium*, *Abies*, *Schizaea pusilla*, *Lycopodium annotinum*, *L. lucidulum*, *L. clavatum*, and *L. obscurum*. However, the spruce percentage from the peat is higher than that recorded at either the Neuse River site or in the Kempsville Formation. Although the spruce data make assignment of the peat to an interglacial a little less certain, it should be emphasized that our knowledge of vegetational changes in the southeast during the Sangamon interglacial is much less nearly complete than our understand-

ing of conditions during the Plum Point and Port Talbot interstadials. It is obvious that conditions would be appropriate for the survival of some boreal taxa at either end of any interglacial sequence.

In summary, the pollen data from the peat horizon exposed in the sections at the Lee Creek Mine suggest clearly that the depositional environment was fresh water rather than brackish and that the peat was probably deposited during a portion of an interglacial rather than during an interstadial.

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# Fossil Woods and Resin-like Substances from the Lee Creek Mine

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ABSTRACT

The spoil heaps at the Lee Creek Mine, near Aurora, Beaufort County, North Carolina, are a source of limited quantities of fossil woods and resin-like substances. The woods are permineralized (Schopf, 1975:29) with quartz in crystalline or opaline form. Eight specimens of the woods were examined for this report. The stratigraphic sources of only three of the eight were established on the bases of foraminiferal assemblages and matrix composition. The specimens came from the lower 4 to 10 feet (1.2 to 3 m) of the early Pliocene Yorktown Formation. The gymnospermous genera *Pinus* Linnaeus, *Juniperus* Linnaeus, and *Taxodium* Richards are identified and the remaining five specimens belong to the angiospermous family Caesalpiniaceae. Their generic identity is tentatively resolved and *Gleditsia* Linnaeus is suggested. The biological source of the resin-like substances has not been determined, nor has the stratigraphic source been established for any but one of the 42 specimens examined. Its occurrence is in the upper lower or lower middle part of the Yorktown Formation at a point higher in the section than that of the woods. Fragments of bark, liquid-filled cavities, quartz-like crystals, and pyrite are the inclusions found in three of the specimens; the others are barren. The identity of the fossil woods with modern genera and species suggests their contemporaniety with the deposition of the sediments in which they are found as opposed to being reworked from older sediments. A better stratigraphic control on the occurrences of the woods in the section, as well as their age relationship to the resin-like substances, remain as the most important objectives in any meaningful, additional studies of these entities found at the Lee Creek Mine.

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## Introduction

Fossil woods can be found in nearly all of the states along the east coast of the United States but never in the quantity nor of the quality of preservation so typical of localities in several of our western states. Most commonly the fossil woods in the east occur as lignitized logs, twigs or drifted fragments and least commonly as permineralized remains. If permineralization is the mode of preservation, quartz is the primary embedding mineral while pyrite, marcasite, limonite, or hematite are secondary in order of occurrence. Calcite is rarely encountered as the preserving agent, except in Pleistocene or Recent tuffs derived from spring deposits.

Fossilized resins, broadly referred to as amber, are found in the Atlantic Coastal Plain. They are restricted in occurrence to the various formations of Cretaceous age ranging geographically from Marthas Vineyard, Massachusetts, southward to near Goldsboro, North Carolina. Most of the specimens are quite small, droplet-like pellets, while larger ones are generally found adhering to or embedded in fragments of lignitized bark or wood. This latter occurrence suggests association of the resin with wounds or wound areas on the

trunks of the source trees. The resin source of the amber has been attributed to gymnosperms, with the exception of one occurrence where analysis indicated an angiosperm source (Langenheim and Beck, 1968:86). The amber at all of the localities is too limited in quantity and quality to be of commercial significance.

For a number of years permineralized wood, with quartz as the embedding mineral, and lumps of thoroughly solidified resin-like substances have been collected from the spoil heaps at the Lee Creek Mine. The number of specimens has never been very great; however, many of the specimens weigh several kilograms. This brief note is based on the study of eight specimens of wood and 42 specimens of resin-like material.

ACKNOWLEDGMENTS.—I wish to express my gratitude to the following collectors who have generously donated to the paleobotanical collections of the National Museum of Natural History specimens of fossil wood and resin-like material from the Lee Creek Mine: Gerard Case, Peter J. Harmatuk, James Kaltenbach, Earl Mason, Jack H. McLellan, Royal Mapes, James G. Mead, Franklin Pearce, Robert Purdy, Clayton E. Ray, Donna Ray, Clyde Swindell, and James Westgate.

I am particularly appreciative of Thomas G. Gibson's help in establishing the horizons from which four specimens (3 fossil wood, 1 resin-like specimen) were obtained.

James P. Ferrigno produced the excellent photographs and photomicrographs. The scanning electron microscope photographs were made possible through the very capable work of Susann Braden and Mary-Jacquelyn Mann of the National Museum of Natural History SEM laboratory.

## Materials and Methods

All of the fossil wood specimens from the Lee Creek Mine thus far donated to the Smithsonian paleobotanical collections, represent silicified, well-eroded, and rounded fragments of secondary wood derived from trunks of trees. No branches, twigs, or shrub-like material have been observed.

Transverse, radial, and tangential sections were obtained by making appropriate cuts of the material with a standard 8-inch (20-cm) diamond saw. The sawed surfaces were ground to smoothness with 600 grit carborundum powder on a glass plate, etched with concentrated hydrofluoric acid for 10 to 30 seconds, carefully rinsed by dipping into several changes of fresh water, air dried, and peeled by means of the Joy, Willis Lacey, technique (1956) using acetone and 76.2 μm (0.003 in) thickness cellulose acetate paper. The resulting peels were mounted in Canada balsam on standard glass microscope slides.

Specimen USNM 267213, *Pinus* species cf. *P. palustris* Miller, is so porous and thoroughly mineralized that it was necessary to prepare standard ground thin-sections that were then stained in acid Bismarck Brown solution in order to differentiate detail. This technique was described by Bartholomew, Matten, and Wheeler, 1970.

The specimens of resin-like substances comprise pieces from 3 × 2 × 1 cm to 30 × 36 × 11.5 cm in overall dimensions. All 42 in the collections at this time represent eroded fragments from larger masses, even in the case of the largest specimen. Ground thin-sections were prepared from one particularly well-banded specimen (USNM 267217) for microscopic study. Epoxy 220 resin was used to attach the sections to standard glass microscope slides, and they were then ground on a glass plate to smoothness and necessary thinness, using water and 1200 grit aluminum oxide. The sections were covered with high-viscosity Canada balsam in order to prevent swelling of the epoxy mounting medium. A glass coverslip was used to seal the mount.

Surfaces of some of the transluscent to transparent resinous specimens were ground and polished to permit better examination of their interiors for possible inclusions. Sanding on a 220 fixed grit belt sander followed by a worn 600 fixed grit belt produced a surface that could then be finished to a high luster, using a soft cloth impregnated with titanium oxide final polishing compound. Unfortunately, although the polish

was bright, it was temporary. The surfaces became dull with any handling and soon became opaque. Freshly broken surfaces showed the same changes with time.

Fragments of plant tissue found in one specimen of the resinous material and portions of mineral-filled cavities in another were attached to aluminum stubs using white glue (Elmer's brand). They were then coated with carbon and gold-palladium to a thickness of ~500 Å, and observed and photographed in a Cambridge Stereoscan Mark II A scanning electron microscope.

### Stratigraphic Occurrence of Specimens

The stratigraphic sources have been established for only four of the fifty specimens considered in this report. Analyses by T.G. Gibson of the foraminiferal assemblages and the sedimentary characteristics of matrix removed from protected cavities in three specimens of the fossil woods and from the fillings of shells of barnacles attached to the surface of one specimen of the resin-like substance (Plate 2: figure 10) are quoted here and serve to date those particular specimens.

Matrix from fossil wood specimen USNM 267218 contained: *Nonionella auris* d'Orbigny, *Elphidium clavatum* Cushman, *Buliminella elegantissima* (d'Orbigny), *Cassidulina laevigata* (d'Orbigny), *Nonion pizarrense* Berry, *Bulimina elongata* d'Orbigny, *Bolivina paula* Cushman and Ponton, *Hanzawaia concentrica* Cushman, *Globigerina falconensis* Blow, small grains of secondary phosphate, and echinoid spines. This assemblage and the sedimentary characteristics indicate that this fossil wood specimen is from the lower part of the Yorktown Formation, in the lower 10 feet (3 m) of the Lee Creek Mine section.

Matrix from fossil wood specimen USNM 298768 contained: *Bulimina elongata* d'Orbigny, *Buccella frigida* (Cushman), *Buliminella elegantissima* (d'Orbigny), *Elphidium clavatum* Cushman, *Cibicides lobatulus* (Walker and Jacob), *Epistominella pontoni* Cushman, *Globigerina bulloides* d'Orbigny, *Hanzawaia concentrica* Cushman, *Bolivina paula* Cushman and Ponton, *Virgulina fusiformis* Cushman, and small grains of secondary phosphate. This assemblage and the sedimentary characteristics indicate that this fossil wood specimen is from the lower part of the Yorktown Formation, in the lower 10 feet (3 m) of the section at the Lee Creek Mine.

The matrix from fossil wood specimen USNM 298767 contained: *Elphidium clavatum* Cushman, *Cibicides lobatulus* (Walker and Jacob), *Cassidulina laevigata* d'Orbigny, *Nonionella auris* d'Orbigny, *Buccella frigida* (Cushman), and medium to large phosphate grains. This assemblage and the sedimentary characteristics indicate that this specimen of fossil wood is probably from within the lower 4 feet (1.2 m) of the Yorktown Formation in the Lee Creek Mine section.

Matrix filling the barnacle shells attached to the specimen of resin-like substance USNM 267220 contained: *Elphidium clavatum* Cushman, *Uvigerina subperegrina* Cushman and Kleinpell, *Buliminella elegantissima* (d'Orbigny), *Cibicides lobatulus* (Walker and Jacob), *Globigerina falconensis* Blow, *Rosalina floridana* Cushman, *Bolivina floridana* Cushman and Ponton, *Nonionella auris* (d'Orbigny), *Lagena substriata* Williamson, *Angulogerina occidentalis* (Cushman), *Bolivina plicatella* Cushman, and echinoid spines. This assemblage and the sedimentary characteristics indicate that this specimen would come from the upper lower to middle part of the Yorktown Formation in the Lee Creek Mine section.

The remainder of the specimens in this study were collected from the spoil heaps of the mine and were either clean when collected or were subsequently washed free of any matrix before donation to the museum collections. As a result no precise stratigraphic occurrence can be established for them.

### Systematics

Division PINOPHYTA
Class PINOPSIDA
Order PINALES
Family PINACEAE

Genus *Pinus* Linnaeus
Family CUPRESSACEAE
Genus *Juniperus* Linnaeus
Family TAXODIACEAE
Genus *Taxodium* Richards
Division MAGNOLIOPHYTA
Class MAGNOLIOPSIDA
Order FABALES
Family CAESALPINIACEAE
Genus *Gleditsia* Linnaeus

## Genus *Pinus* Linnaeus

### *Pinus* species cf. *P. palustris* Miller

PLATE 1: FIGURES 1–5

This description is based on a single specimen (USNM 267213) collected and donated by J. Kaltenbach. It is 17.5 cm long and 9.5 cm wide, the latter dimension measured along the radial section of the wood. Virtually all of the organic matter of the wood has been replaced by quartz. Subsequent leaching by ground water has removed any remaining organic matter and has made the specimen quite porous. The nature of the pitting in the tracheid walls as well as in the cross-field contacts of the ray parenchyma were particularly difficult to demonstrate because of the replication in quartz of the cell walls.

Twelve rather broad growth rings are clearly visible in the cross-section of the wood, the early wood being the broadest and most evenly textured. The late wood is narrower and clearly defined by the presence of numerous longitudinal resin canals (Plate 1: figure 1). There are a few resin canals distributed unevenly through the early wood. The transition from early to late wood is gradual. Rays are very fine and can be seen only where a horizontal resin canal is included in the ray.

Tracheids in cross-section are 22 to 64 μm in diameter (average 35 μm). Bordered pits are found on the radial walls in single rows or less commonly in two rows arranged oppositely (Plate 1: figure 5). No pits were observed on the tracheids in tangential section in the preparations at hand.

Ray parenchyma with one, rarely two, large unbordered pits per cross-field is not well preserved (Plate 1: figure 4). The rays are of two types, uniseriate and fusiform (Plate 1: figure 3) and 1 to 20 cells high (average 8). The fusiform rays contain a horizontal resin canal (Plate 1: figure 3 at arrows). It has not been possible to determine the presence of ray tracheids in this specimen.

The longitudinal resin canals are large, 156 to 180 μm in diameter, and have poorly preserved remains of a thin-walled epithelium lining the walls (Plate 1: figure 2). The horizontal resin canals are much smaller, ranging from 48 to 70 μm in diameter (average 54 μm) and are also lined with an epithelial layer or remnants of tyloses.

Although the cell structure in this specimen is somewhat obscured by the effects of preservation, the detail that has been obtained compares favorably with sections of modern wood of *Pinus palustris* Miller (longleaf pine) from the collections of the Smithsonian Division of Plant Anatomy. Comparison of cell dimensions and clearer detail of ray structure is precluded. The stratigraphic source of this specimen is not known.

## Genus *Juniperus* Linnaeus

### *Juniperus* sp. cf. *J. virginiana* Linnaeus

PLATE 2: FIGURES 1–4

USNM 267215 has distinct growth rings marked by a dense, narrow band of late wood and a less dense broad band of early wood; transition between early and late wood abrupt. Rays are numerous and fine. Parenchyma scattered and gum filled (Plate 2: figure 1). Resin canals not present.

Tracheids small, 23 to 35 μm in diameter; bordered pits in one row on radial walls (poorly preserved) (Plate 2: figure 3 at arrows). Rays uniseriate, low, 1–10 cells high (mostly 4 or 5) (Plate 2: figure 2), homogeneous, cross-field pits single and large (Plate 2: figure 4) or smaller and

paired but more specific details not determined because of poor preservation of the material.

Comparisons of the anatomical details of this specimen with those of sections from modern *Juniperus virginiana* Linnaeus (eastern red cedar) in the collections of the Smithsonian Division of Plant Anatomy suggest close agreement in the identification with that species. Positive identification is precluded by the rather poor preservation of finer anatomical detail in the fossil material.

This specimen was collected by J.H. McLellan and bore his original collection number 237. The fragment is 3.5 × 2.75 × 2.5 cm in overall dimensions. The stratigraphic source of this specimen is not known.

### Genus *Taxodium* Richards

### *Taxodium distichum* Richards

PLATE 1: FIGURES 6–8

USNM 267214 has quite distinct growth rings marked by a narrow band of late wood and a very broad band of early wood. The transition between the early and late wood is abrupt (Plate 1: figure 6). Rays are conspicuous. Parenchyma is scattered randomly through the early wood and is quite obvious because of the dark resinous contents of the individual cells (Plate 1: figure 6).

Tracheids 48 to 68 μm in diameter with bordered pits in single, commonly double, and only occasionally three rows on the radial walls. When in multiples the pits are opposite, and crassulae are present between vertical pairs (Plate 1: figure 8).

Rays are uniseriate, 2 to 13 cells high, composed wholly of parenchyma and exhibit 1 to 3 bordered pits per cross-field area (Plate 1: figure 8).

Longitudinal parenchyma is diffused randomly through the wood and is clearly differentiated from other cells because of the dark material filling the cell lumens (Plate 1: figures 7, 8).

This specimen was collected by C.E. Ray. It is 30.5 × 17.75 × 7.5 cm in overall dimensions. Mineralization of the specimen is more of an opal-like form of quartz rather than the crystalline type found in the other fossil wood samples examined here.

The cellular detail in this specimen is excellently well preserved, and because of this the identification to species (bald cypress) is made with full confidence. Comparison with slides prepared from modern examples of the species housed in the collections of the Smithsonian Division of Plant Anatomy, substantiated the identification. Unfortunately, the horizon from which this specimen was obtained is not known.

### Genus *Gleditsia* Linnaeus

### *Gleditsia* species

PLATE 2: FIGURES 5–7, PLATE 3: FIGURES 1–4

The remaining specimens of fossil wood in this limited study belong to the Magnoliopsida, that is, to dicotyledonous broad-leafed trees. Initial examination of the specimens, following the first cutting with a diamond saw, gave the impression that all of the specimens were identifiable with at most two genera, each one in a different family. Subsequent microscopic examination of cellular detail led to the conclusion that only one genus may be represented from the family Caesalpiniaceae. This family comprises mostly tropical genera; however, our native *Gleditsia* Linnaeus (honey locust) and *Gymnoclaudus* Lamarck (Kentucky coffee tree) are examples of temperate climate members. Of the two genera, *Gleditsia* is the most likely one represented by the fossil woods in the present study. Structural characteristics of each of the specimens overlap so strikingly that they may be identical, and for that reason I have chosen to describe and illustrate only two (USNM 267216 and 267218) of the five specimens representing the Magnoliopsida.

The specimens illustrated by means of photomicrographs of cellulose acetate peel sections in Plate 2: figures 5–7 (USNM 267216) and Plate 3:

figures 1–4 (USNM 267218) were donated by Mr. Peter Harmatuk. Before sectioning, the former was 19 cm long, 8 cm wide, and 5 cm thick. It represents a well-rounded fragment from the trunk of a tree that was at least 66 cm (26 in) in diameter as determined by projecting into a complete circle the arc of the growth rings along the outer margin of the specimen. It was probably a much larger tree. The latter specimen was 28 cm long, 10.5 cm wide, and 3.5 cm thick and represents a fragment of a trunk at least 102.6 cm (40 in) in diameter. The wood is ring porous (Plate 2: figure 5; Plate 3: figure 1) and the transition between early and late wood is abrupt. Vessels are medium- to large-sized, 95–265 μm in diameter, mostly round in cross-section, solitary but forming a band 2 to 5 cells wide in the early wood. Late wood vessels small, 70–100 μm wide, solitary or in small clusters (Plate 3: figure 1). Paratracheal parenchyma conspicuous (Plate 3: figure 1) around vessels and in late wood passing over into the succeeding early wood layer. Vessel members are truncate (Plate 2: figure 7), lack ligulae, and have simple perforation plates (Plate 3: figure 3). Intervascular pitting crowded, angular (Plate 2: figure 7) pits 4.4–5.2 μm in diameter. Rays are high, measured up to 2.4 mm long, multiseriate 4 to 8 cells wide, occasionally uniseriate (Plate 2: figure 6, Plate 3: figure 2), homogeneous and unstoried. A very commonly observed characteristic is the evidence of dark gums filling many of the vessels (Plate 2: figure 5) in large areas of the woods. This is true of all of the specimens examined.

Variation from the discription given above is only slight among the specimens observed. Widths of growth rings, which are quite variable, allow for changes in number of vessels per unit area, minor differences in diameters of the vessels, more prominent parenchyma distribution, at least in wider growth rings, and in some instances the appearance of semi-ring porous structure to the wood. But the microscopic anatomical details remain to unite the group as a whole.

The age of specimen USNM 267216 could not be determined; however, USNM 267218 came from the lower 10 feet of the Yorktown Formation of the Lee Creek Mine. Interestingly, one of the other dated specimens (USNM 298768) came from the same horizon, while USNM 298767 came from the lower 4 feet of the formation.

Comparisons made between the fossil woods and slide preparations of modern woods from the genera *Gleditsia*, *Robinia* Linnaeus, *Gymnocladus* and even *Hymenaea* Linnaeus in the collections of the Division of Plant Anatomy support the assignment of the fossils to *Gleditsia*. The gross, but probably insignificant, variations seen in the fossil woods are not all readily observable in the modern material. The finer anatomical details, however, are supportive to the determination of the genus.

## Resin-Like Substances

The collection of resin-like substances in the Smithsonian from the Lee Creek Mine comprises 42 whole or freshly broken and fragmented specimens. On visual examination, there appear to be four basic forms: (1) transparent, lustrous, yellow to very light reddish brown, approach most closely the appearance of amber; (2) transluscent to nearly opaque, lustrous, massive to well-banded, dark reddish brown (Plate 3: figures 5, 6, 8); (3) opaque, dull to waxy luster, light golden, well banded, and generally with a porous texture (Plate 3: figure 9); and (4) transparent to transluscent on thin edges, waxy luster, very dark brown to black in massive pieces, coarsely banded or swirled patterning.

In all but form 1, the odor of freshly broken or slightly heated surfaces is bituminous and rather unpleasant. In form 1 the odor is not bituminous nor does it have the fragrance characteristic of most ambers when heated. Thus far it has not been possible to define the source or type of organic substances represented by these resin-like materials.

The stratigraphic occurrence of the resin-like substances has been determined for only one specimen (Plate 3: figure 6), USNM 267220, and that is the top lower or lower middle part of the

Yorktown Formation. The specimen is younger than any of the fossil woods from the mine for which ages have been determined.

All of the specimens are fragments of even larger masses as evidenced by the banding that is abruptly truncated at the margins of the specimens (Plate 3: figure 8). The swirled patterns are also in sectional view (Plate 3: figure 9).

It is obvious that the resin-like substances were well solidified before transport into the marine environment of deposition. Evidence of the borings of marine organisms (?Pholadidae) and the attachment of barnacles (*?Chthalmus*) and bryozoans to the surfaces of some specimens is illustrated by specimen USNM 267220 (Plate 3: figures 6, 7, 10).

At the outset of this study the resin-like specimens were examined for inclusions, such as plant debris, insects, and pollen. All of the banded patterning that would suggest inclusion of foreign matter (Plate 2: figure 8; Plate 3: figures 6, 8, 9) has proved to be alternating densities of small spherical bodies (Plate 2: figures 9, 10, 11) that are neither liquid nor gas filled. Instead, they are solid and appear to be a different phase of the resin-like substance itself.

In one specimen, a form 1 type as described above, donated by Mr. Swindell (USNM 267223), fragments of bark were found (Plate 4: figures 1, 2). No identification is possible as to the type of tree from which the bark could have come. It does, however, represent the only inclusion of plant material found in any of the 42 specimens in the study collection and establishes the possibility that the form 1 type of resin-like substance is of plant origin.

Bubble-like cavities are present in most of the specimens in the collection. The cavities usually are empty. However, in one specimen of form 1 material (USNM 267225) the cavities are liquid filled and in another specimen, form 3 material (USNM 267224) quartz-like crystals are present in some of the cavities and pyrite in others (Plate 4: figures 3–7). These liquid and mineral inclusions merit additional study.

The entire collection of resin-like substances will be stored in the paleobotanical collections of the Smithsonian Institution and will be available for additional research to qualified specialists.

## Discussion

At the outset of this study there was hope to establish a relationship between the resin-like substances and the fossil woods found at the Lee Creek Mine. The first assumption that proved wrong was that the woods were permineralized by phosphates. Quartz proved to be the permineralizing agent. The questions arose as to the source of the quartz and why the woods were the only fossil remains to be preserved by that mineral. There were no immediately satisfying answers to these questions. Further the well-rounded nature of the specimens (as if tumbled, perhaps during fluvial transport) and the lack of borings by marine organisms suggest that the woods were silicified elsewhere at an earlier time, then redeposited at the present site. Further, the one piece of resin-like substance that could be dated proved to be younger than any of the dated woods, placing in limbo any possible relationship between the two materials. Thus, when it became apparent that there was no stratigraphic control on most of the specimens at hand, further efforts to identify the woods and analyze the resin-like substances seemed unwarranted.

It would be presumptive to assume that all of the fossil woods and resin-like substances found at the mine were originally from the Yorktown Formation of the Lee Creek section. Some of the specimens have been arbitrarily labelled as from the Pungo River Formation. It is to be hoped that special efforts will be made in further collecting at the mine to obtain specimens of known or determinable stratigraphic occurrence. The analyses of the matrix will establish horizons bearing the wood and resin-like substances and some clear picture may develop that will answer some of the questions posed.

The results of this study suggest that the woods and resin-like substances are probably not much older than the sediments in which they are found. Clearly the woods are identifiable with modern

genera, and, even more significantly, they are close to, if not identical to, modern species. That the resin-like substances are of plant origin still cannot be proved.

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Plates 1–4

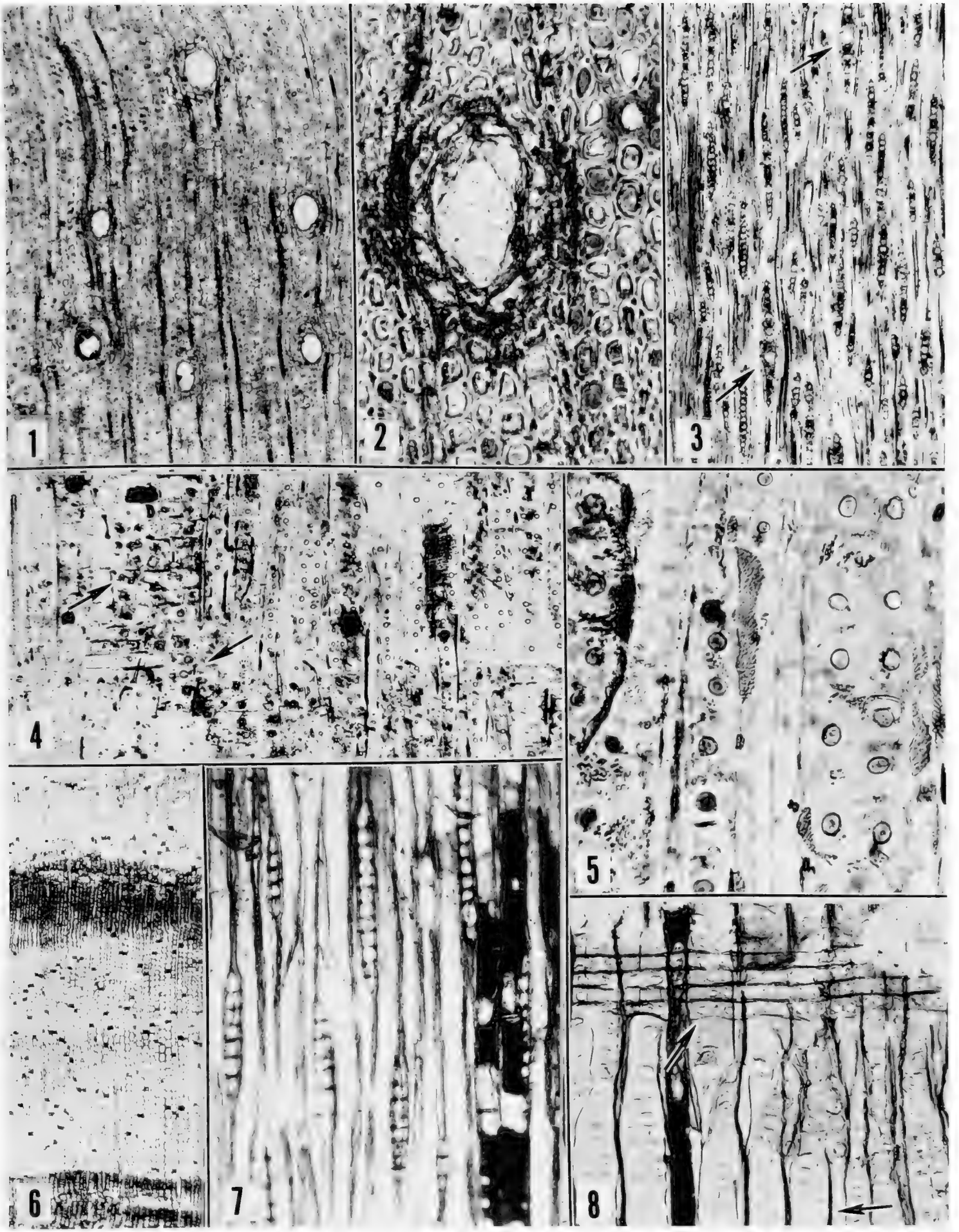
## PLATE 1

*Pinus* species cf. *P. palustris* Miller, USNM 267213

1. Transverse section showing resin canals and general texture of the wood. Growth ring exceeds height of photograph, lower three resin canals mark the end of early and beginning of late wood, × 50.
2. Transverse section of longitudinal resin canal. Thin-walled cells lining the canal are poorly preserved. Radiating fibrilar structure in the canal is mineral growth, × 150.
3. Tangential section showing short, predominantly uniseriate rays except in those rays containing horizontal resin canals (arrows), × 50.
4. Radial section, in which ray cell walls are poorly preserved and accordingly cross-field pitting (arrows) is difficult to illustrate, × 50.
5. Radial section showing single and double rows of circular-bordered pits; pits arranged oppositely when in two rows, × 200.

*Taxodium distichum* Richards, USNM 267214

6. Transverse section showing abrupt change from summer to spring wood. Scattered, resin-filled parenchyma cells are readily visible as dark spots, × 45.
7. Tangential section showing uniseriate rays and resin-filled longitudinal parenchyma, × 145.
8. Radial section showing arrangement of bordered pits, cross-field pits in the ray parenchyma (upper arrow) and crassulae (lower arrow), × 150.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## PLATE 2

*Juniperus* species cf. *J. virginiana* Linnaeus, USNM 267215

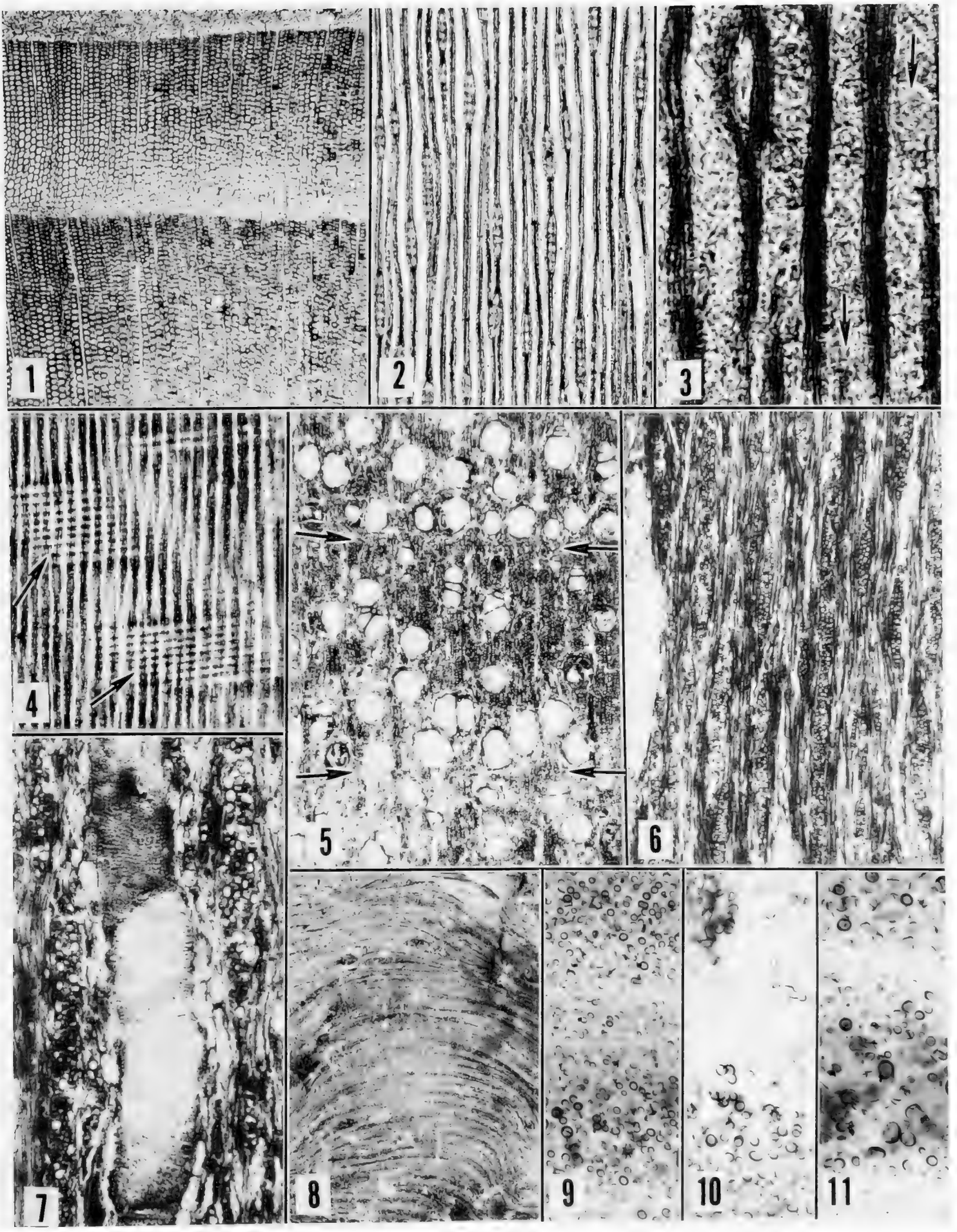
1. Transverse section showing growth rings and general texture of the wood, × 50.
2. Tangential section showing short, uniseriate rays, × 80.
3. Radial section showing remnants of circular bordered pits (arrows) in single rows, × 150.
4. Radial section showing single, large cross-field pits (arrows) in the ray parenchyma, × 80.

*Gleditsia* species, USNM 267216

5. Transverse section showing growth ring (between upper and lower arrows) and general texture of the wood, × 27.
6. Tangential section showing high multiseriate rays, × 40.
7. Tangential section showing truncate vessel members with fine, angular intervascular pitting, × 105.

Resin-like substance, USNM 267217

8. View of broken and eroded surface of resin-like substance showing banding, × 34.
9. Polished thin-section of dense, light-colored band in the specimen showing small spheres; spheres are solids, not liquid or gas, × 250.
10. Polished thin-section of area between dense bands showing diminution of numbers of spheres, representing a clear area in the substance, × 250.
11. Polished thin-section showing variability in sizes and density of numbers of the spheres, which results in the banding of the resin-like substance, × 250.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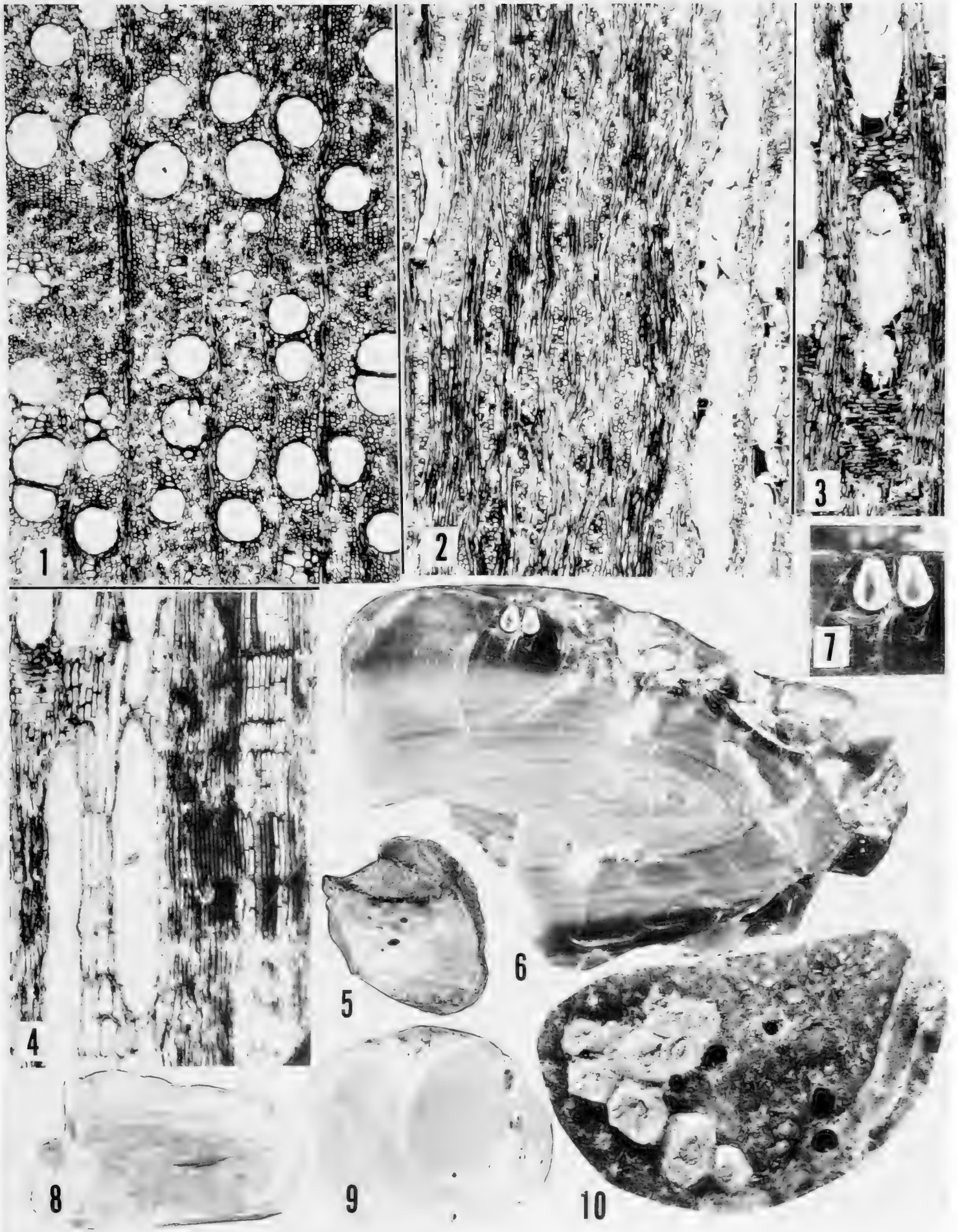
## PLATE 3

*Gleditsia* species, USNM 267218

1. Transverse section showing growth rings and general texture of the wood, × 40.
2. Tangential section showing early vessels (right) and late vessels (upper left), and morphology of the uniseriate and multiseriate rays, × 40.
3. Radial section showing simple perforation plate in vessel member, × 40.
4. Radial section showing storied paratracheal parenchyma associated with vessel members, × 40.

Resin-like substances and associated fauna

5. USNM 267219, lustrous broken surface of nearly homogeneous resin-like substance with large bubble cavities, × 1/2.
6. USNM 267220, broken surface showing luster, color banding and section through borings made by marine organisms (?Pholadidae), × 1.
7. USNM 267220, enlargement of borings seen in figure 6, × 2.
8. USNM 267221, fragment of banded resin-like substance, banding parallel and truncated at ends of specimen, × 1/2.
9. USNM 267222, broken surface of resin-like substance showing peculiar swirled pattern of banding, × 1/2.
10. USNM 267220 (same as in figures 6 and 7) showing barnacles (?*Chthalmus* sp.) attached to the surface of the resin-like substance; bryozoans are also present at the right margin of the specimen, × 2.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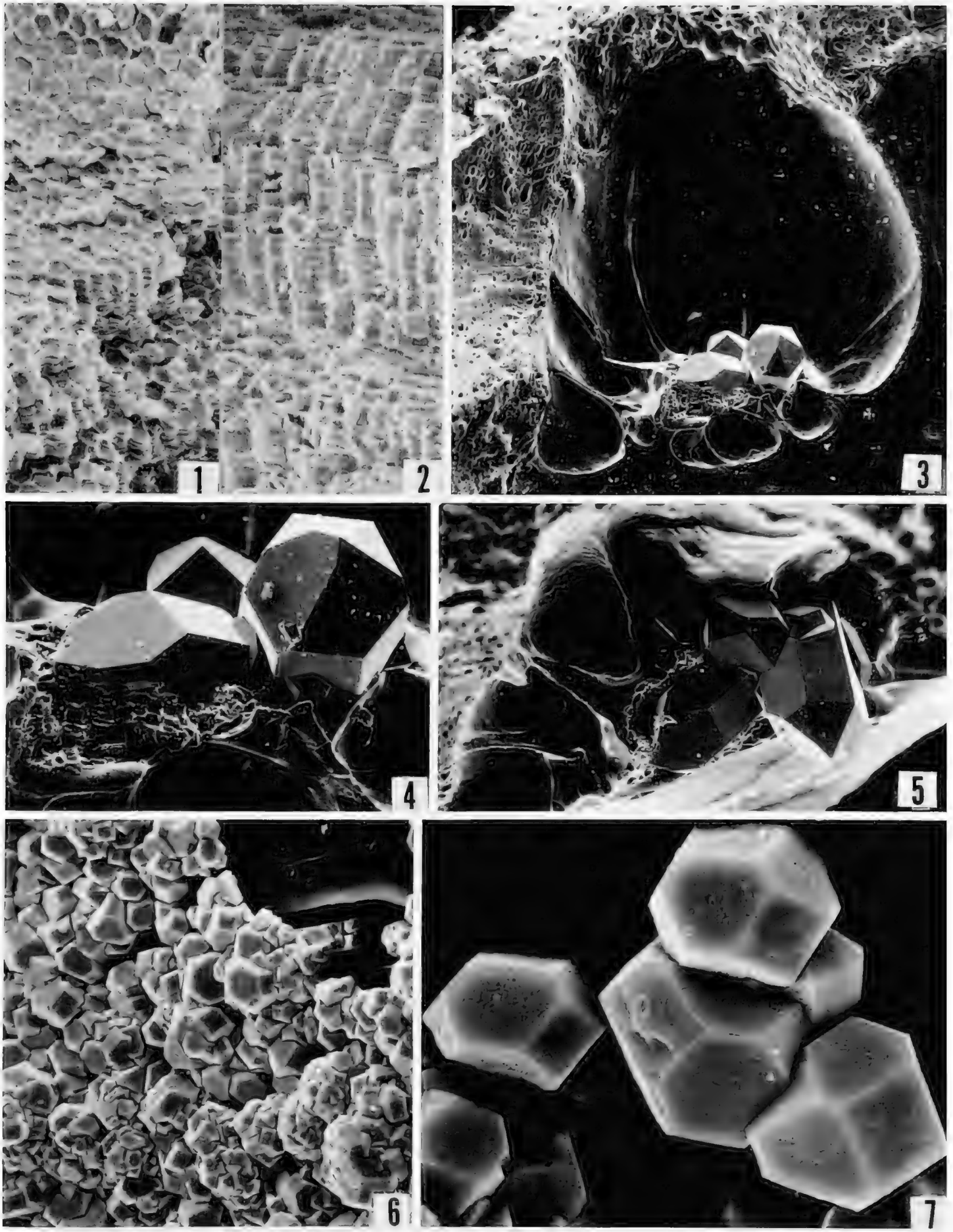
## PLATE 4

Inclusions in resin-like specimens, all SEM photographs

1. USNM 267223, fragment of bark; surface in tangential section, × 250.
2. USNM 267223, same fragment as in figure 1; surface in transverse section, × 249.
3. USNM 267224, quartz-like crystals included in bubble cavity in resin-like substance, × 30.
4. USNM 267224, side view of quartz-like crystals in figure 3, enlarged view, × 85.
5. USNM 267224, vertical view of quartz-like crystals in figure 3, × 38.
6. USNM 267224, pyrite crystals coating inner wall of bubble cavity in resin-like substance, × 620.
7. USNM 267224, pyrite crystals enlarged from same cavity as figure 6, × 3800.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# Biostratigraphy and Paleoecology of a Diatomaceous Clay Unit in the Miocene Pungo River Formation of Beaufort County, North Carolina

*William H. Abbott and John J. Ernissee*

ABSTRACT

The diatomaceous clay unit from two cores from the Pungo River Formation of Beaufort County, North Carolina, contains two diatom assemblages and essentially one silicoflagellate assemblage. Based on the diatom ranges, an age equivalent to Blow's (1969) zones N8–N9 was obtained for the older diatom assemblage and an age equivalent to zone N11 for the younger assemblage. The age range of the silicoflagellate assemblage is inclusive of the diatom assemblages. The diatomaceous clay was deposited in a marine near-shore environment with reducing bottom conditions and nutrient-rich surficial water. The water may have been cooler or upwelling greater during the deposition of the younger assemblage.

## Introduction

Brown (1958) was the first to describe the Miocene sediments of Beaufort County, North Carolina. He considered these Miocene beds to be correlative with the Calvert Formation of Maryland on the basis of Foraminifera at the top of the unit.

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Kimrey (1964) formally designated the Miocene beds of Beaufort County, North Carolina, as the Pungo River Formation. The type section is from a core near Belhaven on the Pungo River in Beaufort County, North Carolina (Figure 1). Kimrey described the lithology of the Pungo River Formation as interbedded phosphatic sands, silts and clays, diatomaceous clays, and phosphatic and nonphosphatic limestones.

The Pungo River Formation was deposited in a northeast-southwest trending basin and varies in thickness from a "feather-edge" east of Washington, North Carolina, to greater than 120 feet (36.5 m) near the Pamlico River in eastern Beaufort County (Kimrey, 1965:6). The phosphorite beds of the Pungo River Formation unconformably overlie the Castle Hayne Limestone of Eocene age, and are unconformably overlain by the Yorktown Formation of Pliocene age.

Gibson (1967) divided the Pungo River section into seven units (Figure 2), with unit 1 at the bottom and unit 7 at the top. On the basis of an abundant planktonic foraminiferal assemblage in the upper 3 meters of the Pungo River Formation, he correlated the uppermost beds of the Pungo River with the *Globigerinatella insueta* zone of Trinidad and Venezuela. Gibson (1967) also correlated Shattuck's (1904) "zone" 10 of the Calvert Formation of Maryland with the *Globigerinatella insueta–Globigerinoides bisphericus* zone of Blow (1959) and the overlying *Globorotalia fohsi barisa-*

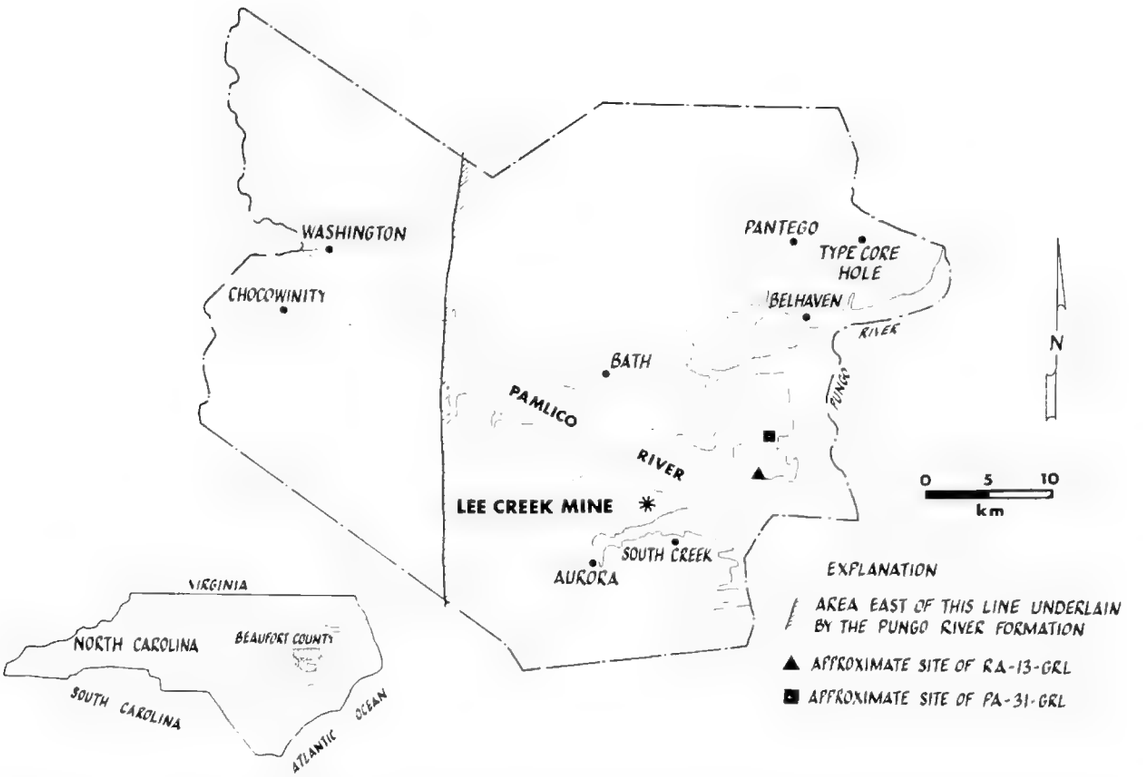


FIGURE 1.—Map showing Pungo River Formation, location of type core, cores used in this study, and the Lee Creek Mine.

*nensis* zone of Bolli (1957). These zones are equivalent to Blow's (1969) zones N8 and N9 and within the Langhian Stage. Gibson (1967, 1971) found that the lower units did not have an adequately preserved foraminiferal assemblage to allow dating, but suggested that molluscan molds from the lower beds had a closer affinity with Oligocene than with Miocene species.

METHODS.—Samples were examined from cores taken in 1962 by the Ground Water Branch of the U.S. Geological Survey, in Beaufort County, North Carolina. These cores were megascopically and microscopically described in great detail by Kimrey (1965). The authors used Kimrey's description to sample siliceous portions of two cores, RA-13-GRL and PA-31-GRL (Figure 1). Though all intervals were not available, enough were obtained to derive a nearly complete sequence of siliceous material. Samples were brought to the laboratory in plastic bags to avoid contamination.

Preparation of samples was done using a modification of Schrader's (1974b) method: the samples are placed in 250 ml beakers in a 1:1 solution of 0.5N HCl and 30–35% hydrogen peroxide. They are heated for approximately 45 minutes; then shaken, and the supernatant liquid poured into 50 ml test tubes for centrifuging.

The samples are centrifuged for 2 minutes at a speed of approximately 1200 revolutions per minute; water with suspended clay minerals is decanted; and the residue re-suspended with distilled water. The procedure of centrifuging, decanting, and washing is repeated 7 times or until the decantate is clear.

The residue is soaked for 5 minutes in a solution of 0.5% sodium pyrophosphate in water shaken thoroughly and centrifuged. This procedure will suspend more of the clay-sized particles. The sodium pyrophosphate solution with suspended clay is decanted, and centrifuging with distilled water is repeated 4 times. The residue is diluted with distilled water and the samples are stored in glass vials. Long-term storage is facilitated by the addition of a few drops of buffered formalin and out of the middle of the bottle two or three drops

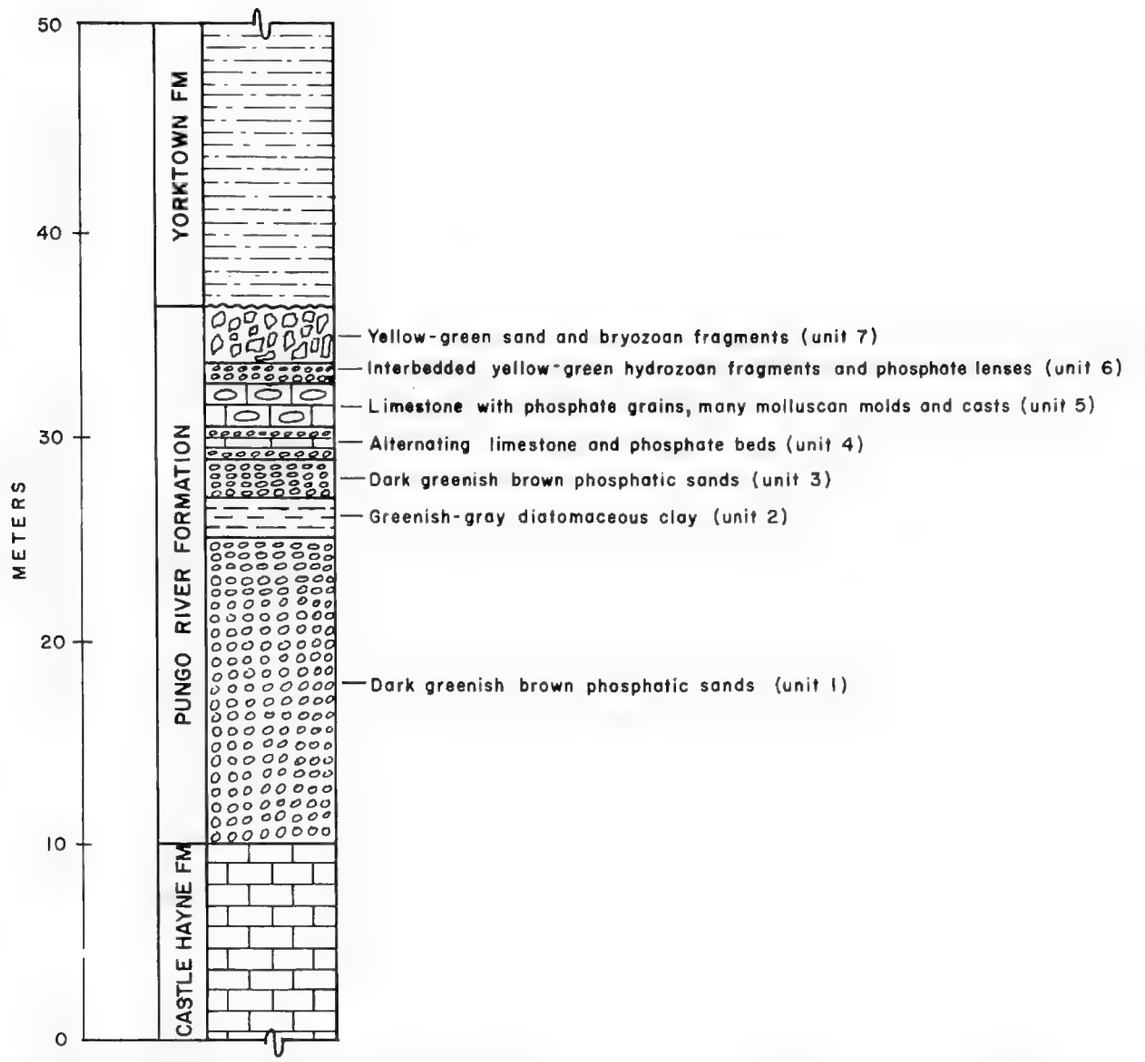


FIGURE 2.—Seven units of the Pungo River Formation, modified from Gibson (1967).

are taken with a disposable bar-straw and placed on a cover glass of 18 × 18 mm. The sample is dried at 45°C. After drying, 1 drop of hyrax is placed on a slide and the cover glass mounted and heated for 5 minutes at approximately 150°C.

Several slides from each sample were scanned with a light microscope to determine the species of diatoms and silicoflagellates present.

ACKNOWLEDGMENTS.—The authors are grateful to Jim Sanpair and Jim Coffee of the Division of Earth Resources, Department of Natural and Economic Resources of North Carolina, who permitted access to the core material and assisted with the sampling. George Andrews and John Barron of the U.S. Geological Survey were extremely helpful with the diatom taxonomy. Many thanks go to Tom Gibson, U.S. Geological Survey, for his help, and to Alan-Jon Zupan, South Carolina Survey, who reviewed the manuscript. Ms. Sharon Huffman and Mrs. Cynthia Johns have been of great assistance in preparing the manuscript, and Camille Ransom in sample preparation. William H. Abbott prepared the diatom floral reference list and John J. Ernissee prepared the silicoflagellate floral reference list.

## Diatomaceous Clays of the Pungo River Formation

Unit 2 of the Pungo River Formation consists of greenish gray diatomaceous clay, which can be traced areally throughout the formation. The authors sampled the diatomaceous unit from

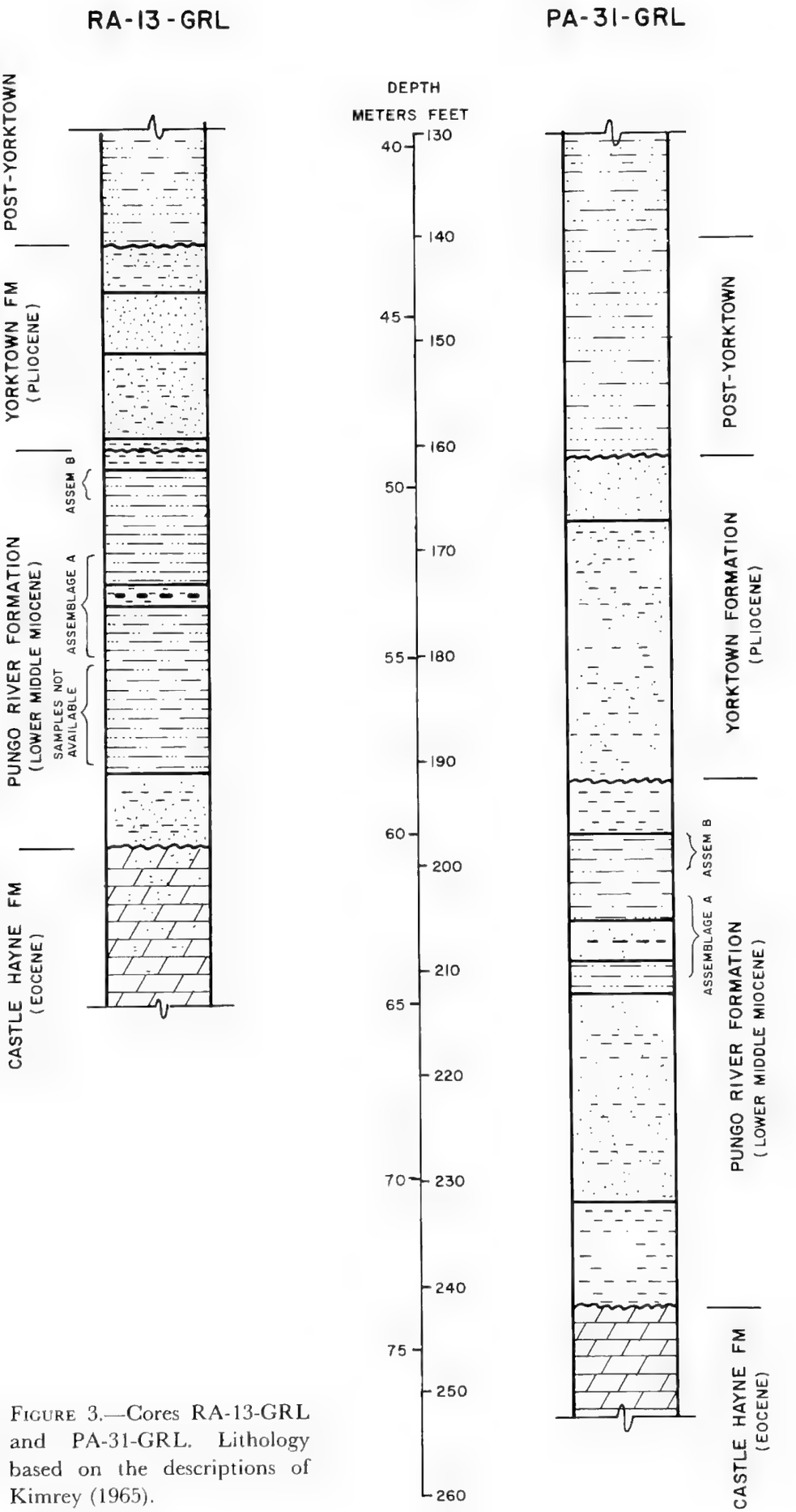


FIGURE 3.—Cores RA-13-GRL and PA-31-GRL. Lithology based on the descriptions of Kimrey (1965).

Kimrey's cores RA-13-GRL and PA-31-GRL (Figure 3), which is considerably thicker than the diatomaceons unit described by Gibson (1967). The diatom assemblage in this unit consists of a well-preserved marine flora (Table 1) containing 55 genera and 114 species of diatoms, of which numerous species characteristic of the Miocene were identified. In addition, a silicoflagellate assemblage of 17 species, as well as many species of ebridians, phytoliths, and endoskeletal dinoflagellates, were observed.

Two distinct diatom assemblages are present. In core RA-13-GRL, diatomaceous samples were taken from 163 to 179 feet (48.9 to 53.7 m). The lower assemblage, assemblage A, was found in the interval between 179 and 174 feet (53.7 and 52.2 m). From approximately 174 to 165 feet (52.2 to 49.5 m), diatoms were sparse and badly broken. The higher assemblage, assemblage B, was encountered in the interval between 165 and 162 feet (49.5 and 48.6 m). Though less well preserved, both diatom assemblages were easily identified in PA-31-GRL (Table 1).

Assemblages A and B share many species in common (Table 1), but important differences also exist. In assemblage B, diatoms typical of coastal upwelling, such as *Thalassionema nitzschiodes*, *Thalassiothrix longissima*, and *Denticula* spp. were very abundant, whereas the same species were sparse in assemblage A. In assemblage A, *Biddulphia tuomeyii*, an extant subtropical species, is quite abundant, but it is not found at all in assemblage B. These diatoms suggest that there are environmental differences between assemblages A and B. It would be difficult to determine what climatic or environmental factors caused the differences other than to say that assemblage B was deposited during a period of greater upwelling of cool nutrient-rich water.

## Biostratigraphy

Stratigraphically, the most significant species of assemblage A are *Raphidodiscus marylandicus* Christian, *Macrora stella* (Azpeitia) Hanna, and *Annellus californicus* Tempère. *Raphidodiscus marylandicus* is restricted to Blow's (1969) zones N8 through N10 (Andrews, 1973; Kanaya and Koizumi, 1970). In addition, *Macrora stella* and *Annellus californicus* are believed to be restricted to zones N8 and N9 or across the early/middle Miocene boundary (Cavallero, 1974; Opdyke, Burckle, and Todd, 1974). Assemblage A of the Pungo River Formation is therefore correlative with Blow's (1969) zones N8 and N9.

Other diatom species that characterize this assemblage are *Actinocyclus ingens* Rattray, *Bruniopsis mirabilis* Karsten, *Cladogramma dubium* Lohman, *Coscinodiscus marginatus* Ehrenberg, *C. perforatus* Ehrenberg, *C. praeyabei* Schrader, *Cussia paleacea* Schrader, *C. praepaleacea* Schrader, *Cymatogonia amblyoceros* Hanna, *Delphineis ovata* Andrews, *D. penelliptica* Andrews, *Denticula hustedtii* Simonsen and Kanaya, *D. lauta* Bailey, *Hemiaulus polymorphus* Grunow, *Mediaria splendida* Sheshukova-Poretskaya, *Rhizosolenia miocenica* Schrader, *Sceptroneis grandis* Abbott, *Stephanopyxis corona* Ehrenberg, *S. lineata* Forti, *S. turris* Ralfs, *Synedra jouseana* Sheshukova-Poretskaya, *Thalassionema nitzschioides* Grunow, *Thalassiothrix longissima* Cleve and Grunow, *Triceratium condecorum* Brightwell, *T. tessellatum* Greville, *Trinaria excavata* Heiberg, and *Trochosira concava* Sheshukova-Poretskaya.

Assemblage B contains several significant diatom species: *Actinocyclus ellipticus* Grunow, *Coscinodiscus lewisianus* Greville, *Rouxia diploneides* Schrader, and *R. naviculoides* Schrader. Both *Actinocyclus ellipticus* and *Coscinodiscus lewisianus* are common in assemblage B. Schrader (1973) in his North Pacific diatom zonation (Figure 4) places the first occurrence of *A. ellipticus* near the top of his zone 20 and the last occurrence of *C. lewisianus* at the base of zone 20 or top of 21. *Actinocyclus ellipticus* was found very near the base of Schrader's zone 20 in the Miocene of South Carolina suggesting that *A. ellipticus* occurs earlier in lower latitudes (Ernissee, Abbott, and Huddlestun, 1977). Also, according to Schrader's zonation, *Rouxia diploneides* becomes extinct in the upper part of NPD zone 21 and *R. naviculoides* makes its first appearance. *Roxia diploneides* and *R. naviculoides* are both found in assemblage B sug-

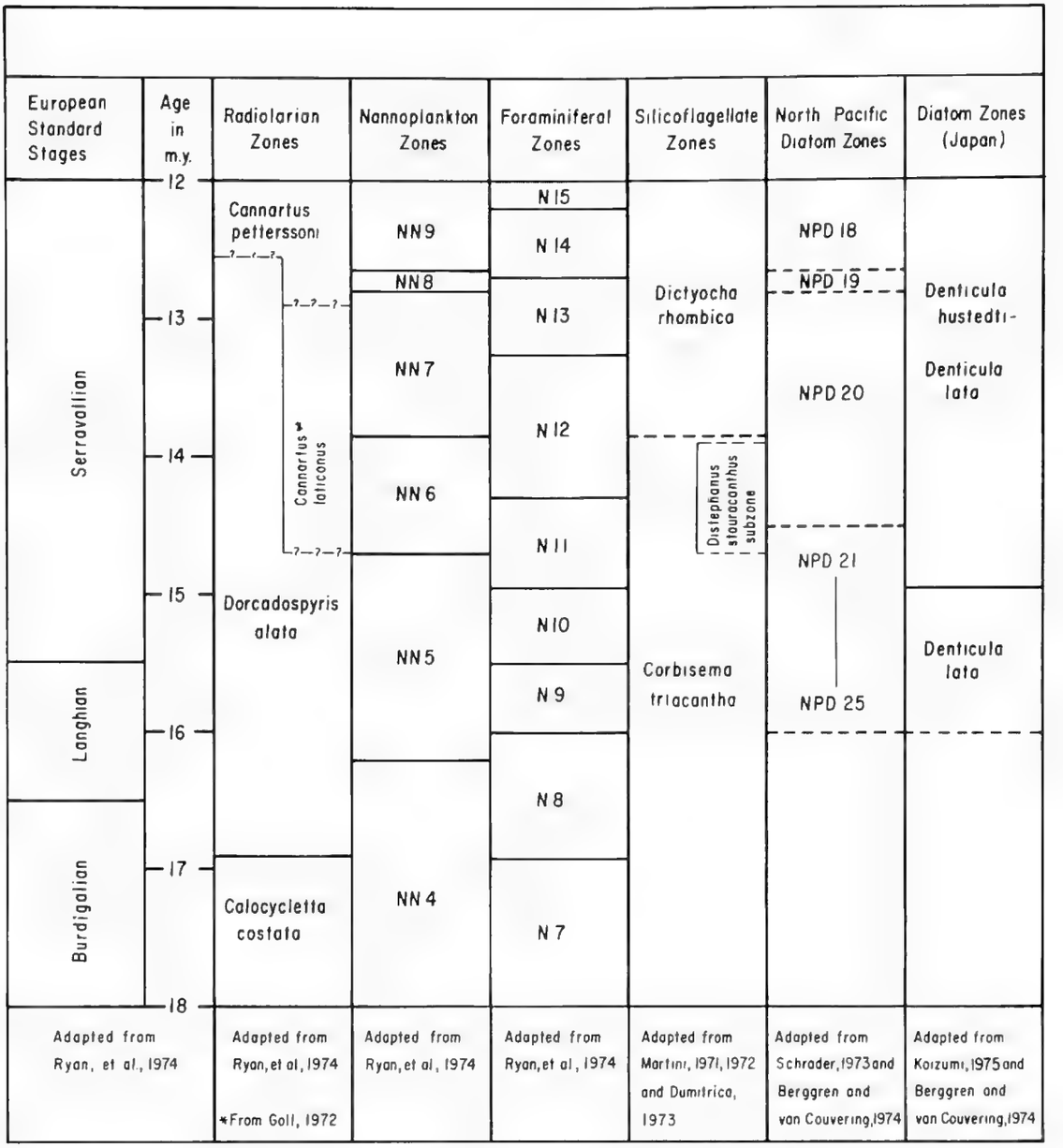


FIGURE 4.—Middle Miocene microfossil correlation chart.

gesting that assemblage B is equivalent to the top of Schrader's NPD zone 21 or at the zone 21/zone 20 boundary. This interval, according to Berggren and Van Couvering (1974:170), is within zone N11 of Blow's (1969) foraminiferal zonation.

Other characteristic species of assemblage B (Table 1) are *Actinocyclus ingens* Rattray, *Bruniopsis mirabilis* Karsten, *Coscinodiscus marginatus* Ehrenberg, *C. perforatus* Ehrenberg, *C. plicatus* Grunow, *C. praeyabei* Schrader, *Cussia paleacea* Schrader, *C. praepaleacea* Schrader, *Cymatogonia amblyoceros* Hanna, *Delphineis angustata* (Pantocsek) Andrews, *D. penelliptica* Andrews, *Denticula hustedtii* Simonsen and Kanaya, *D. lauta* Bailey, *D. nicobarica* Grunow, *Hemiaulus polymorphus* Grunow, *Mediaria splendida* Sheshukova-Poretskaya, *Navicula pennata* Schmidt, *Stephanopyxis corona* Ehrenberg, *S. lineata* Forti, *S. turris* Ralfs, *Synedra jouseana* Sheshukova-Poretskaya, *Thalassionema nitzschioides* Grunow, *Thalassiothrix longissima* Cleve and Grunow, *Triceratium condecorum* Brightwell, *T. tessellatum* Greville, and *Trochosira concava* Sheshukova-Poretskaya.

The silicoflagellate species within the two assemblages are similar, and no stratigraphically significant distinctions between the two assem-

blages can be made (Table 2). Both assemblages are consistent with an assignment to the *Corbisema triacantha* zone as defined by Martini (1971:1696, 1972) and with the subsequent use of that zone by Bukry and Foster (1973, 1974), Dumitrică (1973), and Ciesielski (1975). The upper boundary of the *C. triacantha* zone (Figure 4) has been placed within the nannofossil zone NN6 (Bukry and Foster, 1973) and NN5 (Bukry, 1973). The bottom of the zone occurs roughly at the NN4/3 boundary (Martini, 1972). These would in turn be correlative to middle N12 to N7 of the standard foraminiferal zones (Ryan, 1974). Thus, the silicoflagellate zone assignments are inclusive of the diatom assignments.

*Distephanus stauracanthus* Ehrenberg, which occurs only in samples from PA-31-GRL, 198′ and 205′, does permit much tighter control on those samples because of its narrow range. Martini (1971, 1972) and Dumitrică (1973) suggest that this species is confined entirely within the NN6 nannofossil zone and would, therefore, be correlative to the N11–lower part of N12 foraminiferal zones (Ernissee, Abbott, and Huddlestun, 1977).

The silicoflagellate assemblages from the Pungo River Formation samples, particularly those of RA-13-GRL, show all but two of the species illustrated in Tynan's (1957) paper on the Calvert Formation of Maryland, and suggest close age correlation with that deposit. However, Tynan's samples are confined to Shattuck's (1904; Tynan, 1957, fig. 1) zones 3 through 10, which is essentially the lower two-thirds of the Calvert Formation. The stratigraphically significant *Distephanus stauracanthus* is absent from Tynan's samples, however, and only a broad time-correlation is possible.

## Paleoenvironment

Microfossils in the Pungo River diatomaceous clay unit suggest a definite marine environment with no indication of freshwater forms. The diatoms in both assemblages A and B include many coastal, neritic, and littoral forms that could be found along the present Atlantic coastline. The presence of oceanic, pelagic diatoms and silicoflagellates indicates open marine circulation.

As previously noted (p. 291) diatoms typical of coastal upwelling are extremely prevalent in assemblage B and, though present, not as abundant in assemblage A. In assemblage B, *Biddulphia tuomeyii*, a subtropical species, is a dominant form in the assemblage. This species is commonly found along the coast of the Carolinas today. If the extinct species were eliminated from assemblage A, then the assemblage would not be very different from a modern coastal assemblage at the same latitude.

Coastal upwelling apparently increased considerably during the time of deposition of assemblage B, bringing cooler nutrient-rich waters into the area. This may have been the result of changing wind patterns, changing ocean currents, or both.

The clastic component of both assemblages is predominantly microfossil remains with some clay. Therefore, the basin in which these diatomaceous clays were deposited appears to have been sediment-starved.

The abundance of benthic diatoms suggests that water depth was not greater than that to which light could penetrate. Since light penetration is dependent upon water turbidity caused by sediment suspension and also by productivity, it is impossible to estimate actual depth.

As in Miocene sediments of South Carolina (Abbott, 1974a, 1975), both assemblages A and B contained opaline phytoliths similar to those found in prairie grasses. These opaline phytoliths (Abbott, 1975) suggest that climatic conditions were drier during Pungo River time (lower-middle Miocene) than the present. This is further supported by the presence of hickory and abundant oak pollen with an absence of pine pollen (James Darrell, Georgia Southern College, Statesboro, pers. comm., 1976).

Rooney and Kerr (1967) suggest that the Pungo River Formation was deposited in a shallow marine basin characterized by a reducing environment, with the presence of pyroclastic material. Our data do not support the finding of

TABLE 1.—Diatom data (X = present in both assemblages, A = in assemblage A only, B = in assemblage B only)

| Species | RA-13-GRL | | | | | | | PA-31-GRL | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 179′ | 177′9″ | 176′ | 175′ | 171′ | 164′8″ | 163′8″ | 210′ | 205′ | 198′ |
| *Actinocyclus ellipticus* | | | | | | B | B | | | B |
| *A. ingens* | | X | X | X | | X | X | X | X | X |
| *A. octonarius* | X | X | X | X | X | X | | X | X | X |
| *A. tenellus* | X | | X | X | | X | | X | X | X |
| *Actinoptychus marylandicus* | | | | | | | B | | B | B |
| *A. senarius* | X | X | X | X | X | X | X | X | X | X |
| *A. virginicus* | | | | | | | | | | B |
| *Anaulus mediterraneus* var. *intermedia* | | | X | | | | X | | | |
| *Annellus californicus* | A | A | | | | | | | | |
| *Asteromphalus robustus* | X | | | | | | | | X | X |
| *Biddulphia aurita* | X | | X | X | | X | | X | X | |
| *B. tuomeyii* | A | A | A | A | | | | A | | |
| *Bruniopsis mirabilis* | | | X | | | X | X | X | | |
| *Cladogramma dubium* | | | | A | | | | A | | |
| *Clavicula polymorpha* var. *aspicephala* | X | X | X | X | | X | X | X | X | X |
| *Coscinodiscus apiculatus* | X | X | X | X | X | X | | X | | |
| *C. asteromphalus* | X | X | | X | X | | | | X | |
| *C. curvatulus* | | X | X | X | | X | | X | X | |
| *C. gigas* var. *diorama* | X | | | X | | X | | | X | |
| *C. lewisianus* | | | | | | B | B | | B | B |
| *C. marginatus* | X | X | | X | X | X | X | | X | X |
| *C. monicae* | | | X | | | X | | | | |
| *C. nitidus* | | | | | | B | B | | | |
| *C. nodulifer* | X | X | | | | X | X | | X | X |
| *C. oculus-iridis* | X | | X | X | | X | X | | X | X |
| *C. perforatus* | X | X | X | X | | | X | X | | X |
| *C. perforatus* var. *cellulosa* | X | | | | | | | | | X |
| *C. plicatus* | | | | | | B | B | | | B |
| *C. praeyabei* | | | X | X | | X | X | X | X | X |
| *C. rothii* | X | | X | X | | X | | | X | X |
| *C. stellaris* | X | | X | X | X | X | X | X | X | X |
| *C. vetustissimus* | | | | | | X | X | X | X | X |
| *Cosmiodiscus elegans* | | | | | | B | | | | |

| Species | RA-13-GRL | | | | | | | PA-31-GRL | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 179′ | 177′9″ | 176′ | 175′ | 171′ | 164′8″ | 163′8″ | | | |
| *Paralia complexa* | X | X | X | X | | X | X | X | X | X |
| *P. sulcata* | X | X | X | X | X | X | X | X | X | X |
| *P. sulcata* var. *coronata* | X | X | X | X | X | X | X | X | X | X |
| *Periptera tetracladia* | X | | X | X | | X | X | X | X | X |
| *Pleurosigma affine* var. *marylandica* | X | X | X | | | X | X | X | X | X |
| *Pseudodimerogramma elliptica* | X | X | | X | | | | X | X | X |
| *Pseudopyxilla americana* | X | | X | | X | X | | X | | X |
| *Pyxilla johnsoniana* | | A | A | | | | | A | | |
| *Raphidodiscus marylandicus* | A | A | A | A | | | | A | | |
| *Rhaphoneis affinis* | X | X | X | X | | X | X | X | | X |
| *R. biseriata* | | | X | | | X | X | | X | X |
| *R. elegans* | X | X | X | X | X | X | X | X | X | X |
| *R. gemmifera* | X | X | | X | | X | | X | | X |
| *R. parilis* | | | | | | | | | B | B |
| *R. rhombica* | | X | X | X | | | | | | |
| *Rhizosolenia bergonii* | | | | | X | | | | | X |
| *R. miocenica* | | X | | | | | | X | X | |
| *Rouxia californica* | | | | | | B | | | | |
| *R. diploneides* | | | | | | B | B | | | |
| *R. naviculoides* | | | | | | B | | | | |
| *R. yabei* | | | | | | | B | | | B |
| *Sceptroneis grandis* | A | A | A | A | A | | | A | | |
| *Stephanogonia actinoptychus* | X | X | X | X | X | X | | X | X | X |
| *Stephanopyxis corona* | X | | X | X | | X | X | X | X | X |
| *S. grunowii* | | X | | | | | X | | X | |
| *S. lineata* | X | X | X | X | X | X | X | X | X | X |
| *S. turris* | X | X | X | X | X | X | X | X | X | X |
| *Stictodiscus kittonianus* | X | | X | X | X | X | X | X | X | X |
| *Synedra jouseana* | X | X | X | X | X | X | X | X | X | X |
| *Thalassionema nitzschioides* | X | X | X | X | X | X | X | X | X | X |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Craspedodiscus coscinodiscus* | | | | | | B | | | B | B |
| *Cussia paleacea* | X | | | | X | | X | | | X |
| *C. praepaleacea* | | | | X | | | | X | | X |
| *Cyclotella kelloggi* | | | | | | B | | | | |
| *Cymatogonia amblyoceros* | X | X | X | X | | X | X | X | X | |
| *Cymatosira andersoni* | | X | X | X | | X | X | | | X |
| *C. immunis* | X | X | X | X | | | | X | X | |
| *Cymatosira* sp. A | | | X | X | | X | | | | |
| *Delphineis angustata* | | | | | | X | X | X | X | X |
| *D. lineata* | X | X | | X | | | | X | X | X |
| *D. novaecaesaraea* | | | | | X | X | X | X | X | X |
| *D. ovata* | A | A | A | A | | | | A | | |
| *D. penelliptica* | X | X | X | X | | X | X | X | X | |
| *Denticula hustedtii* | X | X | X | X | X | X | X | X | X | X |
| *D. lauta* | X | | X | X | | X | X | X | X | X |
| *D. nicobarica* | | | | | | B | B | | B | |
| *D. norwegica* | X | X | X | X | | X | | X | | X |
| *D. punctata* | | | | | | | B | | | |
| *Dicladia pylea* | | X | | X | | X | X | X | | X |
| *Diploneis crabro* | | | | | | | B | | B | B |
| *Diploneis* sp. A | | | | | | | | | B | B |
| *Dossetia hyalina* | | | | X | | | | X | | |
| *Endictya robusta* | X | | | X | X | X | | | | |
| *Goniothecium rogersii* | X | X | X | X | | X | | X | | X |
| *Hemiaulus cf. polymorphus* | X | | X | X | | X | | X | X | X |
| *Hyalodiscus laevis* | X | X | X | X | X | X | | X | X | |
| *Liradiscus asperulus* | X | X | X | X | | X | X | X | X | X |
| *L. bipolaris* | | | | X | X | X | X | | | X |
| *L. ovalis* | X | X | X | X | | X | X | X | X | X |
| *Lithodesmium minusculum* | X | | X | X | | X | X | | X | X |
| *Macrora stella* | A | A | | A | | | | | | |
| *Mediaria splendida* | X | X | X | X | | X | X | | X | X |
| *Melosira westii* | X | | | | X | X | X | X | X | X |
| *Navicula directa* | X | X | X | X | X | | X | | X | X |
| *N. hennedyii* | | | | X | | X | | | | |
| *N. pennata* | | | | | | B | B | | B | |
| *Nitzschia* sp. B | X | | X | X | | | | X | X | |
| *Thalassiosira* sp. A | X | | X | X | | X | X | X | | |
| *Thalassiosira* sp. B | X | | | | | | | | | |
| *Thalassiothrix longissima* | X | X | X | X | | X | X | X | X | X |
| *Triceratium condecorum* | X | X | X | X | | X | X | X | X | X |
| *T. subrotundatum* | X | X | X | X | | X | X | | | X |
| *T. tessellatum* | | X | X | X | | X | | X | | |
| *Trinacria excavata* | | | A | A | | | | A | | |
| *Trochosira concava* | X | X | X | X | | X | | X | X | |
| *Xanthiopyxis* spp. | X | X | X | X | X | X | X | X | X | X |

TABLE 2.—Silicoflagellate data (x = present)

| Species | RA-13-GRL | | | | | | | PA-31-GRL | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 179′ | 177′9″ | 176′ | 175′ | 171′ | 164′8″ | 163′8″ | 210′ | 205′ | 198′ |
| *Cannopilus binoculus* | X | X | X | X | | X | | X | X | X |
| *C. haeckelii* | X | X | X | X | | X | X | X | | X |
| *C. hemisphaericus* | X | X | X | X | X | X | X | X | | |
| *C. sphaericus* | | X | | X | X | X | X | X | X | X |
| *C. triommata* | X | X | X | X | | X | X | X | X | X |
| *Cannopilus* sp. A | | | X | | | | X | | | |
| *Cannopilus* sp. B | X | | | | | X | X | X | | |
| *Corbisema triacantha* | X | X | X | X | X | X | X | X | X | X |
| *Dictyocha fibula*, sensu lato | X | X | X | X | X | | X | X | X | X |
| *D. rhombica*, sensu lato | X | X | X | X | X | X | X | X | X | X |
| *Dictyocha* sp. A | | | | | | | | | X | X |
| *Dictyocha* sp. B | | | | | | | | | X | X |
| *Distephanus crux* | X | X | X | X | X | X | X | X | X | X |
| *D. speculum*, sensu lato | | X | | X | X | X | X | X | X | X |
| *D. speculum* var. *pentagonus* | | | | | | X | X | | | |
| *D. stauracanthus* | | | | | | | | | X | X |
| *Halicalyptra picassoi* | | | | | X | X | X | | | |
| *Mesocena* cf. *M. elliptica* | X | | X | | | | X | X | X | X |

pyroclastic material, but the observation of thin rhythmites within the diatomaceous clay does suggest reducing bottom conditions.

## Conclusions

In examining a diatomaceous clay unit found in two cores, RA-13-GRL and PA-31-GRL, from the Pungo River Formation of North Carolina, the authors found two distinct diatom assemblages in two different intervals, but a nearly homogeneous silicoflagellate assemblage throughout both intervals. The older assemblage, assemblage A, contains *Raphidodiscus marylandicus* Christian, *Macrora stella* (Azpeitia) Hanna, and *Annellus californicus* Tempère, suggesting an age equivalence to Blow's (1969) foraminiferal zones N8 and N9. The younger assemblage, assemblage B, contains *Actinocyclus ellipticus* Grunow, *Coscinodiscus lewisianus* Greville, *Rouxia diploneides* Schrader, and *R. naviculoides* Schrader, suggesting in comparison with Schrader's (1973) zonation, that this assemblage is equivalent to Blow's (1969) zone N11.

The silicoflagellate data place both assemblages in Martini's (1971, 1972) *Corbisema triacantha* zone, which is equivalent to Blow's (1969) zones N7–N12, thus being inclusive of the diatom assignments. Though the silicoflagellate production was quite varied, no further zonation could be assigned with this group except for two samples of assemblage B from PA-31-GRL, which were placed in Blow's zone N11 on the basis of the diatoms. *Distephanus stauracanthus* occurs in these two samples and suggests that assemblage B is in the *D. stauracanthus* zone of Dumitrică (1973), which is equivalent to Blow's (1969) zones N11 to lower N12.

If the diatomaceous clay studied in RA-31-GRL and PA-13-GRL is equivalent to Gibson's (1967) unit 2, then the age of N8–N9 for assemblage A is in agreement with the N8–N9 age obtained by Gibson (1967, 1971) for the Pungo River Formation. However, no strata of zone N11 age were reported from the Pungo River Formation by Gibson. Recently, in cores from a locality north of Gibson's (1967) study area and the area of this study, Gibson (pers. comm., 1976) has found planktonic Foraminifera of zone N11 age in Pungo River strata.

It appears then that there were at least two periods of deposition represented within the lower-middle Miocene Pungo River Formation, one approximately during Blow's zone N8–N9, and one during zone N11. This is similar to the situation in South Carolina (Ernissee, Abbott, and Huddlestun, 1977) where a diatomaceous unit within the Hawthorn Formation has been dated the equivalent of upper zone N11 to lower zone N12 on the basis of diatoms, silicoflagellates, planktonic Foraminifera, and nannoplankton. The diatom assemblage in the South Carolina unit appears to be just slightly younger than that in the Pungo River Formation, but uncomformably overlies older Miocene sediments.

The diatom and silicoflagellate assemblages suggest that the environment of deposition of this unit was a near-shore environment with open marine circulation and reducing bottom conditions. Water temperatures during assemblage A time were probably very much like those of the present, with some upwelling. During the time that assemblage B was deposited, coastal upwelling had increased, and water temperatures were probably cooler. The presence of large numbers of opaline phytoliths from prairie grasses may be indicative of a somewhat drier continental climate. This is supported by the lack of pine pollen and presence of oak and hickory pollen.

## Diatom Floral Reference List

Taxa are listed alphabetically in much the same manner as used by Schrader (1973). Species are listed in alphabetical order to simplify their location. If illustrated, the plate and figure numbers are beneath the species name. Rather than describing all species, only those which are new and those for which there is no easily accessible description will be described. In most cases, an attempt has been made to list a standard or recent reference from which a detailed description

and synonymy may be obtained.

Responsibility for all designations and descriptions of diatom species in this paper is that of the senior author and, therefore, new species of diatoms or new combinations will include only his name. Holotypes of new species are placed in the Botany Department of the National Museum of Natural History, Smithsonian Institution, Washington, D.C.

### Genus *Actinocyclus* Ehrenberg, 1838

*Actinocyclus ellipticus* Grunow in van Heurck, 1881 [1880–1885]
Illustration: Plate 6: figures 2, 3.
Description: Hustedt, 1930:533, fig. 303.

*Actinocyclus ingens* Rattray, 1890
Illustration: Plate 4: figures 3, 4.
Description: Kanaya, 1971:554, numerous figures; Koizumi, 1968: 207–208, pl. 32: figs. 5–6.

*Actinocyclus octonarius* Ehrenberg, 1838
Illustration: Plate 6: figure 1.
Description: Hustedt, 1930:53 as *A. Ehrenbergii*; Andrews, 1976: 14, pl. 3: fig. 7.
Discussion: There is some debate over this species name. *A. octonarius* is used here, following Hendey, 1937:262, and Lohman, 1942:77.

*Actinocyclus tenellus* (Brébisson) Andrews, 1976
Illustration: Plate 7: figure 3.
Description: Hustedt, 1930:530, fig. 302, as *A. Ehrenbergii var. tenella* (Brébisson); Andrews, 1976:14, pl. 3: figs. 8, 9.

### Genus *Actinoptychus* Ehrenberg, 1843

*Actinoptychus marylandicus* Andrews, 1976
Description: Andrews, 1976:14, pl. 4: figs 3–6.

*Actinoptychus senarius* (Ehrenberg) Ehrenberg, 1843
Illustration: Plate 7: figure 1.
Description: Hustedt 1930:475–478, fig. 264.

*Actinoptychus virginicus* (Grunow) Andrews, 1976
Illustration: Plate 7: figure 2.
Description: Andrews, 1976:15, pl. 4: figs. 9–12.

### Genus *Anaulus* Ehrenberg, 1844

*Anaulus mediterraneus* var. *intermedia* Grunow in van Heurck, 1882 [1880–1885]
Description: Hendey, 1964:11, pl. 26: fig. 6.

### Genus *Annellus* Tempère, 1908

Description: Tempère in Tempère and Peragallo, 1908.

*Annellus californicus* Tempère in Tempère and Peragallo, 1908
Description: Tempère in Tempère and Peragallo, 1908:60; Hanna, 1932:172, pl. 4: figs. 5–9.

### Genus *Asteromphalus* Ehrenberg, 1844b

*Asteromphalus robustus* Castracane, 1875
Illustration: Plate 18: figure 3.
Description: Hustedt, 1930:496–498, fig. 278.

### Genus *Biddulphia* Gray, 1821

*Biddulphia aurita* (Lyngbye) Brébisson and Godey, 1838
Description: Hustedt, 1930:846–849, figs. 500–502.

*Biddulphia toumeyii* (Bailey) Roper, 1859
Illustration: Plate 10: figures 5, 6.
Description: Hustedt, 1930:834–836, fig. 491; Andrews, 1976:17, pl. 5: fig. 11.

### Genus *Bruniopsis* Tempère, 1928

Description: Tempère in Karsten, 1928.

*Bruniopsis mirabilis* (Brun) Karsten, 1928
Illustration: Plate 17: figure 5.
Description: As *Brightwellia* (?) *mirabilis* Brun in Brun and Tempère, 1889:27, pl. 8: fig. 1; *Bruniopsis mirabilis* Kolbe, 1954:24, pl. 4: fig. 44; Kanaya, 1971:555.

### Genus *Chaetoceros* Ehrenberg, 1844b

*Chaetoceros* species was represented in the assemblages as fragments or spores (Plate 18: figure 2) such as those found in the genera *Dicladia* and *Xanthiopysis.*

### Genus *Cladogramma* Ehrenberg, 1854

*Cladogramma dubium* Lohman, 1948
Description: Lohman, 1948:168, pl. 9: fig. 5; Sheshukova-Poretskaya, 1967:192, pl. 24: fig. 6, pl. 29: fig. 4.

### Genus *Clavicula* Pantocsek, 1886

*Clavicula polymorpha* var. *aspicephala* Pantocsek, 1886
Illustration: Plate 13: figure 5.
Description: Pantocsek, 1886:37, pl. 2: fig. 15.

### Genus *Coscinodiscus* Ehrenberg, 1838

*Coscinodiscus apiculatus* Ehrenberg, 1844a
Illustration: Plate 2: figures 3, 4.
Description: Hustedt, 1930:449–452, fig. 248; Andrews 1976:10, pl. 2: fig. 3.

*Coscinodiscus asteromphalus* Ehrenberg, 1844a
Illustration: Plate 3: figure 3.
Description: Hustedt, 1930:416, fig. 223; Hendey, 1964:78, pl. 24: fig. 2.

*Coscinodiscus curvatulus* Grunow in Schmidt et al., 1878 [1874–1959].
Illustration: Plate 1: figure 1.
Description: Hustedt, 1930:406–410; Andrews, 1976:10, pl. 2: fig. 4.

*Coscinodiscus gigas* var. *diorama* Grunow, 1884
Illustration: Plate 1: figure 3.
Description: Wornardt, 1967:24, fig. 25.

*Coscinodiscus lewisianus* Greville, 1866
Illustration: Plate 6: figures 4, 5.
Description: Kanaya, 1971:555, pl. 40.5: figs. 4–6.

*Coscinodiscus marginatus* Ehrenberg, 1843
Illustration: Plate 1: figure 2.
Description: Hustedt, 1930:416–418, fig. 223; Andrews, 1976:11, pl. 2: figs. 6, 7.

*Coscinodiscus monicae* (Grunow) Rattray, 1889
Description: Rattray, 1889:563; Hanna, 1932: 182, pl. 9: fig. 2; Kanaya, 1971, pl. 40, fig. 2.

*Coscinodiscus nitidus* Gregory, 1857
Description: Hustedt, 1930:414–416, fig. 221.

*Coscinodiscus nodulifer* Schmidt, 1878
Illustration: Plate 3: figure 4.
Description: Hustedt, 1930:426–427, fig. 229; Schrader, 1973:703.

*Coscinodiscus oculus-iridis* Ehrenberg, 1841
Description: Hustedt, 1930:454–456, fig. 252; Andrews, 1976:11, pl. 2: fig. 8.

*Coscinodiscus perforatus* Ehrenberg, 1844a
Illustration: Plate 2: figures 1, 2
Description: Hustedt, 1930:445–449, fig. 245; Andrews, 1976:11, pl. 2: fig. 9.

*Coscinodiscus perforatus* var. *cellulosa* Grunow, 1884
Description: Hustedt, 1930:447, fig. 246; Andrews, 1976:11, pl. 2: fig. 10.

*Coscinodiscus plicatus* Grunow, 1884
Illustration: Plate 4: figure 1.
Description: Kolbe, 1954:34–35; Schrader, 1973:703, pl. 6: fig. 23.
Discussion: Specimens of *C. plicatus* found in the Pungo River Formation differ from *C. plicatus* of younger sediments by having finer areolation (9 in 10 microns). This species has the marginal spines of *C. plicatus*, which are much more prominent than any I have seen on younger material. It may be that the *C. plicatus* of the Pungo River Formation will warrant separation as a new species.

*Coscinodiscus praeyabei* Schrader, 1973
Illustration: Plate 4: figure 2.
Description: Schrader, 1973:703, pl. 6: fig. 16, pl. 7: figs. 17–20, 22, 23.

*Coscinodiscus rothii* (Ehrenberg) Grunow, 1878
Illustration: Plate 3: figure 1.
Description: Hustedt, 1930:400–406, fig. 211; Andrews, 1976:12, pl. 3: figs. 1, 2.

*Coscinodiscus stellaris* Roper, 1858
Illustration: Plate 3: figure 2.
Description: Hustedt, 1930:396–398, fig. 207.

*Coscinodiscus vetustissimus* Pantocsek, 1886
Illustration: Plate 1: figure 4.
Description: Hustedt, 1930:412, fig. 220; Andrews, 1976:12, pl. 3: fig. 3.

### Genus *Cosmiodiscus* Greville, 1866

*Cosmiodiscus elegans* Greville, 1866
Illustration: Plate 8: figure 2.
Description: Fricke in Schmidt et al., 1901 [1874–1959] pl. 229: figs. 10, 11; Barron, 1975:137, pl. 7: fig. 20.

### Genus *Craspedodiscus* Ehrenberg, 1844b

*Craspedodiscus coscinodiscus* Ehrenberg, 1844a
Illustration: Plate 8: figure 1.
Description: Kolbe, 1954:36, pl. 1: fig. 4; Kanaya, 1971:555, pl. 40.4: figs. 1–3.

### Genus *Cussia* Schrader, 1974*

*Cussia paleacea* (Grunow) Schrader, 1974a
Illustration: Plate 12: figure 2.
Description: Under the name *Coscinodiscus paleaceus*, in Schrader 1973:703, pl. 3: figs. 10–12; 1974a:543, fig. 1, photos 11–14.
*Cussia praepaleacea* Schrader, 1974
Illustration: Plate 12: figure 3.
Description: Under the name *Coscinodiscus praepaleaceus*, in Schrader, 1973:703, pl. 3: figs. 1–9.

### Genus *Cyclotella* Kützing, 1834

*Cyclotella kelloggi* Hanna, 1932
Description: Hanna, 1932:185, pl. 10: figs. 2–4; Wornardt, 1967:33, fig. 46.

### Genus *Cymatogonia* Grunow, 1883

*Cymatogonia amblyoceros* (Ehrenberg) Hanna, 1932
Illustration: Plate 7: figures 4, 5.
Description: Hanna, 1932:186, pl. 10: fig. 5.

### Genus *Cymatosira* Grunow, 1862

*Cymatosira andersoni* Hanna, 1932
Illustration: Plate 12: figure 5.
Description: Hanna, 1932:187, pl. 10: fig. 6.
*Cymatosira immunis* (Lohman) Abbott, new combination
Illustration: Plate 12: figure 4.
Description: Lohman, 1948:182, pl. 11: fig. 6; Andrews, 1976:21, pl. 7: fig. 3 as *Rhaphoneis immunis* Lohman.
Discussion: This species was originally placed in the genus *Rhaphoneis* by Lohman (1948). Observation of numerous specimens of this species have led this author to believe that it is not a *Rhaphoneis*. Andrews (pers. comm., 1975) has suggested that it may be a *Cymatosira*. This species often shows a trend transitional towards *Cymatosira andersoni* and is found in chains in girdle view. Since *Cymatosira* seems a more logical place for *immunis*, this new combination is established.
*Cymatosira immunis* var. A Abbott, new status
Illustration: Plate 12: figure 6.
Discussion: The author will be looking at this problematic specimen again at a later date. It differs from *C. immunis* in that it is a more broadly obovate form with apiculate apices.

### Genus *Delphineis* Andrews, 1977

*Delphineis angustata* (Pantocsek) Andrews, 1977
Description: Andrews, 1977, pl. 1: figs. 1–4; pl. 2: figs. 21, 22; pl. 3: figs. 29, 30; Sheshukova-Poretskaya, 1967:241–242, pl. 41: fig. 8.
*Delphineis lineata* Andrews, 1977
Illustration: Plate 13: figure 9.
Description: Andrews, 1977, pl. 1: figs. 5–7.
*Delphineis novaecaesarea* (Kain and Schultze) Andrews, 1977
Illustration: Plate 13: figure 10.
Description: Andrews, 1977, pl. 1: figs. 8–11; pl. 2: figs. 23, 24; pl. 3: figs. 31, 32; Lohman, 1948:184, pl. 11: figs. 4, 5.
*Delphineis ovata* Andrews, 1977
Description: Andrews, 1977, pl. 1: figs. 12–15; pl. 2: figs. 25, 26; pl. 4: figs. 33, 34.
*Delphineis penelliptica* Andrews, 1977
Illustration: Plate 11: figure 6.
Description: Andrews, 1977, pl. 1: figs. 16–20; pl. 2: figs. 27, 28; pl. 4: figs. 35, 36.

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* Since completion of this paper, it has been learned that *Cussia* is a junior synonym of *Rossiella* Desikachary and Maheshwari, 1958.

### Genus *Denticula* Kützing, 1844*

*Denticula hustedtii* Simonsen and Kanaya, 1961
Illustration: Plate 13: figure 8.
Description: Simonsen and Kanaya, 1961:501, pl. 1: figs. 19–25, pl. 2: figs. 36–47.
*Denticula lauta* Bailey, 1854
Description: Simonsen and Kanaya, 1961:500–501, pl. 1: figs. 1–8.
*Denticula nicobarica* Grunow, 1868
Illustration: Plate 13: figure 7.
Description: Simonsen and Kanaya, 1961:503, pl. 1: fig. 11–13.
*Denticula norwegica* Schrader in Schrader and Fenner, 1976
Illustration: Plate 14: figure 5.
Description: Schrader in Schrader and Fenner, 1976:963, 978, pl. 1: fig. 38.
*Denticula punctata* Schrader, 1973
Description: Schrader, 1973:705, pl. 1: figs. 25–30, pl. 3: figs. 16, 17.

### Genus *Dicladia* Ehrenberg, 1844a

Discussion: Species of this genus are probably spores of *Chaetoceros*.

*Dicladia pylea* Hanna and Grant, 1926
Description: Hanna and Grant, 1926:142, pl. 16: figs. 4, 5.

### Genus *Diploneis* Ehrenberg, 1840

*Diploneis crabro* (Ehrenberg) Ehrenberg, 1854
Illustration: Plate 14: figure 7.
Description: Hustedt, 1937:616–626, fig. 1028; Andrews, 1976:23, pl. 7: figs. 22, 23.
*Diploneis* sp. A
Discussion: There are taxonomic problems with this species which will be dealt with at a later date.

* Since the completion of this paper, the genus *Denticulopsis* Simonsen, 1979, has been established and includes all of the species listed here under *Denticula*.

### Genus *Dossetia* Azpeitia, 1911

*Dossetia hyalina* Andrews, 1976
Illustration: Plate 18: figure 1.
Description: Andrews, 1976:19, pl. 6: figs. 4–7.

### Genus *Endictya* Ehrenberg, 1845b

*Endictya robusta* (Greville) Hanna and Grant, 1926
Illustration: Plate 16: figure 2.
Description: Wornardt, 1967:31, figs. 40, 41.

### Genus *Goniothecium* Ehrenberg, 1843

*Goniothecium rogersii* Ehrenberg, 1843
Illustration: Plate 16: figures 3, 4.
Description: Hanna, 1932:192, pl. 11: figs. 4–6; Andrews, 1976:17, pl. 5: figs. 12, 13.

### Genus *Hemiaulus* Ehrenberg, 1844b

*Hemiaulus* cf. *polymorphus* Grunow, 1884
Illustration: Plate 17: figure 4.
Description: Hustedt, 1930:880–881, figs. 525–526.

### Genus *Hyalodiscus* Ehrenberg, 1845

*Hyalodiscus laevis* Ehrenberg, 1845b
Illustration: Plate 5: figure 5.
Description: Hustedt, 1930:294–295, fig. 135; Andrews, 1976:14, pl. 4: figs. 1, 2.

### Genus *Liradiscus* Greville, 1865

*Liradiscus asperulus* Andrews, 1976
Illustration: Plate 17: figure 2.
Description: Andrews, 1976:16, pl. 5: figs 3–5.
*Liradiscus bipolaris* Lohman, 1948
Illustration: Plate 17: figure 1.
Description: Lohman, 1974:346, pl. 4: fig. 11.
*Liradiscus ovalis* Greville, 1865
Description: Andrews, 1976:16, pl. 5: figs. 6,7.

### Genus *Lithodesmium* Ehrenberg, 1840

*Lithodesmium minusculum* Grunow in van Heurck, 1883 [1880–1885]

Illustration: Plate 15: figure 6.
Description: Schrader, 1973:706, pl. 12: figs. 7(?), 15, 17.

### Genus *Macrora* Hanna, 1932

*Macrora stella* (Azpeitia) Hanna, 1932
Illustration: Plate 15: figure 8.
Description: Hanna, 1932:196, pl. 12: fig. 7.

### Genus *Mediaria* Sheshukova-Poretskaya, 1962

*Mediaria splendida* Sheshukova-Poretskaya, 1962
Illustration: Plate 13: figure 4.
Synonym: *Trachyspehenia australis* Jousé, 1959.
Description: Sheshukova-Poretskaya, 1967:306, pl. 47: fig. 14, pl. 48: fig. 8.

### Genus *Melosira* Agardh, 1824

*Melosira westii* W. Smith, 1856
Illustration: Plate 5: figure 3.
Description: Andrews, 1976:8, pl. 1: figs. 1, 2.

### Genus *Navicula* Bory, 1824

*Navicula directa* (W. Smith) Ralfs in Pritchard, 1861
Illustration: Plate 14: figure 2.
Description: Hendey, 1964:202; Abbott, 1974: 314, pl. 7M.
*Navicula hennedyii* W. Smith, 1856
Illustration: Plate 14: figure 1.
Description: Hustedt, 1964:453–464, figs. 1516–1523; Andrews, 1976:22, pl. 7: figs. 17, 18.
*Navicula pennata* A. Schmidt, 1876 [1874–1959]
Illustration: Plate 14: figure 3.
Description: Hendey, 1964:203, pl. 30: fig. 21; Andrews, 1976:22–23, pl. 7: figs. 20, 21.

### Genus *Nitzschia* Hassal, 1845

*Nitzschia* species B
Illustration: Plate 14: figure 4.
Discussion: Valves are linear with parallel sides and broadly rounded apices. Costae average 11 in 10 microns. This species resembles *N. curta* (van Heurck) Hustedt.

### Genus *Paralia* Heiberg, 1863

*Paralia complexa* (Lohman) Andrews, 1976
Illustration: Plate 5: figure 2.
Description: Hustedt, 1930:276–279, fig. 119; Andrews, 1976:8, pl. 1: figs. 3, 4.
*Paralia sulcata* (Ehrenberg) Cleve, 1873
Synonym: *Melosira sulcata* (Ehrenberg) Kützing (1844).
Illustration: Plate 5: figure 1.
Description: Hustedt, 1930:276–279, fig. 119; Andrews, 1976:8, pl. 1: figs. 5, 6.
*Paralia sulcata* var. *coronata* (Ehrenberg) Andrews, 1976
Synonym: *Melosira sulcata* forma *coronata* Grunow.
Illustration: Plate 5: figure 4.
Description: Hustedt, 1930:276, fig. 119d; Andrews, 1976:9, pl. 1: figs. 7, 8.

### Genus *Periptera* Ehrenberg, 1845a

*Periptera tetracladia* Ehrenberg, 1845a
Description: Hanna 1932:205, pl. 13: fig. 8; Andrews, 1976:19, pl. 5: figs. 20, 21.
Discussion: This species is probably a spore of *Chaetoceros*.

### Genus *Pleurosigma* W. Smith, 1852

*Pleurosigma affine* var. *marylandica* Grunow in Cleve and Grunow, 1880
Illustration: Plate 14: figure 6.
Description: Andrews, 1976:23, pl. 7: fig. 24.

### Genus *Pseudodimerogramma* Schrader, 1976.

Description: Schrader in Schrader and Fenner, 1976:993.

*Pseudodimerogramma elliptica* Schrader in Schrader and Fenner, 1976
Illustration: Plate 11: figure 5.
Description: Schrader in Schrader and Fenner, 1976:963, 993, pl. 3: fig. 5.

### Genus *Pseudopyxilla* Forti, 1909

*Pseudopyxilla americana* (Ehrenberg) Forti, 1909
Illustration: Plate 15: figure 7.
Description: Forti, 1909:30, pl. 1: figs. 6, 7; Sheshukova-Poretskaya, 1967:226, pl. 39: fig. 2; Andrews, 1976:19, pl. 6: figs. 9–12.

### Genus *Pyxilla* Greville, 1865

*Pyxilla johnsoniana* Greville, 1865
Illustration: Plate 15: figure 4.
Description: Forti, 1909:31; pl. 2: fig. 2.
Discussion: This species was not uncommon in assemblage A but was generally broken. *P. johnsoniana* is probably an Oligocene species reworked into this assemblage.

### Genus *Raphidodiscus* H.L. Smith, 1887

*Raphidodiscus marylandicus* Christian, 1887
Illustration: Plate 8: figures 3, 4.
Description: Hanna, 1932:208–210, pl. 14: figs. 3–4; Andrews, 1973:231–243.

### Genus *Rhaphoneis* Ehrenberg, 1844

*Rhaphoneis affinis* Grunow in Pantocsek, 1886
Illustration: Plate 11: figure 4.
Description: Grunow in Pantocsek, 1886:5, pl. 27: fig. 266.
*Rhaphoneis biseriata* Grunow in Pantocsek, 1886
Description: Andrews, 1975, pl. 1: fig. 7.
*Rhaphoneis elegans* (Pantocsek and Grunow) Hanna, 1932
Illustration: Plate 11: figure 3.
Description: Hanna, 1932:213, pl. 15: figs. 5–7; Andrews, 1975:208, pl. 2: figs. 25–27.
*Rhaphoneis gemmifera* Ehrenberg, 1844a
Illustration: Plate 11: figure 1.
Description: Lohman, 1948:181, pl. 11: fig. 1; Andrews, 1975, pl. 2: figs. 28, 29, pl. 4: figs. 56–60, pl. 5: figs. 69, 70.
*Rhaphoneis parilis* Hanna, 1932
Description: Hanna, 1932:214, pl. 16: figs. 2–4; Andrews, 1975, pl. 3: figs. 41–44.
*Rhaphoneis rhombica* (Grunow) Andrews, 1975
Illustration: Plate 11: figure 2.
Description: Andrews, 1975, pl. 2, figs. 33, 34.

### Genus *Rhizosolenia* Ehrenberg, 1841

*Rhizosolenia bergonii* H. Peragallo, 1892
Description: Hustedt, 1930:575–576, fig. 327; Schrader, 1973:709, pl. 9: figs. 1–5, 7, 8, 10, 12, 22, 23, pl. 10: figs. 24, 29.
*Rhizosolenia miocenica* Schrader, 1973
Illustration: Plate 15: figure 5.
Description: Schrader, 1973:709, pl. 10: figs. 2–6, 9–11.

### Genus *Rouxia* Brun and Héribaud, 1893

Description: Brun and Héribaud in Héribaud Joseph, 1893.
*Rouxia californica* M. Peragallo in Tempère and Peragallo, 1910
Illustration: Plate 15: figure 2.
Synonym: *R. peragalli* Brun and Héribaud, in Tempère and Peragallo (1909:117), *R. peragalli* f. *californica* (M. Peragallo) Sheshukova-Poretskaya (1967:295).
Description: Hanna, 1930:186–188, pl. 14: figs. 6–7.
*Rouxia diploneides* Schrader, 1973
Illustration: Plate 15: figure 3.
Description: Schrader, 1973:710, pl. 3: figs. 24, 25.
*Rouxia naviculoides* Schrader, 1973
Description: Schrader, 1973:710, pl. 3: figs. 27–32.
*Rouxia yabei* Hanna, 1930
Illustration: Plate 15: figure 1.
Synonyms: *Rouxia peragalli* f. *yabei* (Hanna) Sheshukova-Poretskaya (1967:295, pl. 43: fig. 18), *Rouxia peragalli* Brun and Héribaud, in Héribaud Joseph (1893, pl. 1: figs. 12b,c).
Description: Hanna, 1930:185, pl. 14: figs. 2–4.

### Genus *Sceptroneis* Ehrenberg, 1844

*Sceptroneis grandis* Abbott, new species
Illustration: Plate 11: figure 7, Plate 12: figure 1.

Synonym: *Sceptroneis caduceus* Ehrenberg of Hanna (1932:216–217, pl. 16: figs. 5–7).

Description: This species is an elongated, subcuneate form up to 200 microns long and 17 microns wide. The valve face is covered by large puncta (3 in 10 microns). There is a distinct pseudoraphe. The transverse striae are not aligned across the pseudoraphe. The median portion of the valve is slightly inflated with the inferior apex slightly cuneate. The superior apex is rostrate-capitate and has a radiating pore field of very small puncta. The holotype (Plate 11: figure 7), with a length of 199 microns and a width of 17 microns, has been placed in the Botany Department of the National Museum of Natural History, Smithsonian Institution, Washington, D. C.

Discussion: This species was figured by Hanna (1932) from the Sharktooth Hill deposit as *Sceptroneis caduceus* Ehrenberg. There is very little similarity between the two species other than general outline. The punctae of *S. grandis* average 3 in 10 microns whereas those of *S. caduceus* average 4 in 10 microns. The original figure of *S. caduceus* is redrawn in Hustedt (1931:130, fig. 651). Pantocsek (1886:34, pl. 3: fig. 30, pl. 25: fig. 224) figured and described a species called *Rhaphoneis hungarica*, which is similar to Hanna's *S. caduceus* and to the species described here. It is Abbott's opinion that this species has close affinity to *Sceptroneis* but not to *S. caduceus*.

### Genus *Stephanogonia* Ehrenberg, 1845a

*Stephanogonia actinoptychus* (Ehrenberg) Grunow in Van Heurck, 1882

Illustration: Plate 5: figure 6.

Description: Andrews, 1976:19, pl. 6: fig. 8.

### Genus *Stephanopyxis* Ehrenberg, 1845a

*Stephanopyxis corona* (Ehrenberg) Grunow in Van Heurck, 1882 [1880–1885]

Description: Andrews, 1976:9, pl. 1: figs. 11, 12.

*Stephanopyxis grunowii* Grove and Sturt in Schmidt et al., 1888 [1874–1959]

Illustration: Plate 9: figures 1, 2.

Description: Proschkina-Lavrenko, 1949:39; Barron, 1975:155, pl. 12: fig. 15.

*Stephanopyxis lineata* (Ehrenberg) Forti, 1912

Illustration: Plate 9: figure 5.

Description: Andrews, 1976:9, pl. 1: figs. 13, 14,

*Stephanopyxis turris* (Greville and Arnott) Ralfs in Pritchard, 1861

Illustration: Plate 9: figures 3, 4.

Description: Hustedt, 1930:304–307, figs. 140–144; Andrews, 1976:10, pl. 2: figs. 1, 2.

### Genus *Stictodiscus* Greville, 1861a

*Stictodiscus kittonianus* Greville, 1861c

Illustration: Plate 16: figure 1.

Description: Sheshukova-Poretskaya, 1967:182, pl. 26: fig. 9; Barron, 1975:156.

### Genus *Synedra* Ehrenberg, 1832

*Synedra jouseana* Sheshukova-Poretskaya, 1962

Illustration: Plate 13: figure 3.

Description: Schrader, 1973:710, pl. 23: figs. 21–23, 25, 38.

### Genus *Thalassionema* Grunow, 1881

*Thalassionema nitzschioides* Grunow in van Heurck, 1881 [1880–1885]

Illustration: Plate 13: figure 2.

Description: Hustedt, 1932:244–246, fig. 725; Hasle and Mendiola, 1967:111, figs. 5, 27–34, 39–44.

Discussion: There is considerable variation in this species. Similar levels of variation have often resulted in naming numerous new species or varieties. The author can see no purpose in subdividing *T. nitzschioides* in the Pungo River material.

### Genus *Thalassiosira* Cleve, 1873

Discussion: The two species of this genus that were collected are not common and are problematic. They are here designated species A and B, and will be dealt with at a later date.

### Genus *Thalassiothrix* Cleve and Grunow, 1880

*Thalassiothrix longissima* Cleve and Grunow, 1880
Illustration: Plate 13: figure 1.
Description: Cupp, 1943:184, fig. 134; Andrews, 1976:21, pl. 7: figs. 9, 10.

### Genus *Triceratium* Ehrenberg, 1841

*Triceratium condecorum* Ehrenberg, 1845a
Illustration: Plate 10: figure 2.
Synonym: *Triceratium interpunctatum* Grunow in Schmidt et al., 1882 [1874–1959], pl. 76: fig. 7.
Description: Hanna 1932:221, pl. 17: figs. 1, 3; Andrews, 1976:18, pl. 5: figs. 18, 19.
*Triceratium subrotundatum* Schmidt in Schmidt et al., 1886 [1874–1959]
Illustration: Plate 10: figure 4.
Description: Schmidt in Schmidt et al., 1886 [1874–1959], pl. 93: fig. 1.
*Triceratium tessellatum* Greville, 1861
Illustration: Plate 10: figure 3.
Description: Lohman, 1948:176, pl. 10, fig. 3.

### Genus *Trinacria* Heiberg, 1863

*Trinacria excavata* Heiberg, 1863
Illustration: Plate 10: figure 1.
Description: Hustedt, 1930:887–888, fig. 532.

### Genus *Trochosira* Kitton, 1871

*Trochosira concava* Sheshukova-Poretskaya, 1967
Illustration: Plate 17: figure 3.
Description: Sheshukova-Poretskaya, 1967: 138, pl. 11: fig. 7, pl. 13: fig. 3.

### Genus *Xanthiopyxis* Ehrenberg, 1845a

Discussion: In the Pungo River Formation, there are a great many variations of specimens which could be placed under *Xanthiopyxis*. These probably are, in most cases, spores of the genus *Chaetoceros*, and no attempt was made in this study to separate them into species.

## Silicoflagellate Floral Reference List

This section is a preliminary listing only and cannot be considered an exhaustive taxonomic study. In preparing this list, I have followed the precedent of Martini (1971) in using a simplified species concept for several of the taxa. This will be indicated by the term "sensu lato" following the species name. *Dictyocha fibula*, sensu lato, is taken as including all forms with a 4-sided basal ring, with four radial spines and an apical bar parallel to the major axes of the basal ring. *D. rhombica*, sensu lato, is likewise a 4-sided basal ring as *D. fibula* but with the apical rod in the transverse position. These species concepts are similar to those of Martini (1971:1697). *Distephanus crux*, sensu lato, which has a 4-sided basal ring with four radial spines and a single apical window includes a wide variation in forms. Again, no attempt was made to subdivide this taxon. Similarly, in agreement with the work of Ling (1970:100–103; 1972:173, 177–178) the Mesocenoid forms found in this study are lumped together as *Mesocena* cf. *M. elliptica*. The content adopted for the taxa will be apparent from the illustrations. I do not believe that the stratigraphic correlations discussed earlier would be affected significantly by further subdivision of the taxa as listed. It is my hope to do a more detailed taxonomic study of these samples in the future.

The format followed here is the same as that of the diatom section. In most cases an attempt has been made to list a standard or recent reference from which a detailed description and synonymy may be obtained. The most useful compilation is that of Loeblich et al. (1968).

### Genus *Cannopilus* Haeckel, 1887

Emendation: Dumitrică, 1973.

*Cannopilus binoculus* (Ehrenberg) Lemmermann, 1901
Illustration: Plate 19: figures 1, 2.
Description: Lemmermann, 1901:267, pl. 11: fig. 22; Mandra and Mandra, 1972:7, 13, figs. 1–11.

*Cannopilus haeckelii* Lemmermann, 1901
Illustration: Plate 19: figures 3, 4.
Description: Lemmermann, 1901:267, pl. 11: fig. 26; Mandra and Mandra, 1972:13–14, figs. 12–16.

*Cannopilus hemisphaericus* (Ehrenberg) Haeckel, 1887
Illustration: Plate 19: figures 5, 6; Plate 20: figures 1, 2.
Description: Haeckel, 1887:1569.
Discussion: Considerable controversy surrounds this taxon and a great many varieties of individuals have been assigned to it (See Ling, 1970:99–100; Dumitrică, 1973:853–854). The content adopted for this species is that of Perch-Nielsen (1975:685, pl. 1: fig. 10–12; Ling, 1972:147–149, pl. 23: fig. 1–4, not 5; and Dumitrică, 1973:853–854, pl. 10: fig. 6.

*Cannopilus sphaericus* Gemeinhardt, 1931
Illustration: Plate 20: figures 3, 4.
Description: Gemeinhardt, 1931:105, pl. 10: figs. 3, 4 (fide Loeblich, et al., 1968:29, 68, 202).
Discussion: This relatively large form is readily recognizable by the large number of apical windows, the highly domed shape, the basal horns which generally number 7 or 8 and which point downward from the plane of the basal ring, and by the equal number of lateral windows to radial spines; the lateral windows are generally much larger than the windows of the rest of the apical apparatus (Plate 20: figures 3, 4). The content chosen for this taxon is similar to that of Dumitrică, 1973:854, pl. 11: figs. 1, 2, not 3–5; Perch-Nielsen, 1975, pl. 1: figs. 1–5.

*Cannopilus triommata* (Ehrenberg) Lemmermann, 1901
Illustration: Plate 20: figure 5; Plate 21: figure 1.
Description: Lemmermann, 1901:267, pl. 11: fig. 25; Mandra ad Mandra, 1972:14, 17, fig. 46.

*Cannopilus* species A
Illustration: Plate 21: figure 2.
Description: This large species was found as single specimens in sample RA 13-176′ and RA 13-163′8″. It has an 8-sided basal ring with 8 equal-length basal horns in the same plane as the basal ring. The specimen illustrated has 8 basal accessory spines, relatively large apical windows and two prominent apical accessory spines. The basal ring size suggest close approximation to *C. schulzii*; however, the number of apical windows is much greater.

*Cannopilus* species B
Illustration: Plate 21: figure 3.
Description: This species differs from *Cannopilus* sp. A by the larger number of relatively smaller apical windows. It appears that it would also have 8 or 9 basal horns. The apical apparatus is not nearly as domed as in *C. sphaericus*.

### Genus *Corbisema* Hanna, 1928

*Corbisema triacantha* (Ehrenberg) Hanna, 1931
Illustration: Plate 21: figures 4–8.
Description: Hanna, 1931:198, pl. D (fide Loeblich et al., 1968:30, 116); Ciesielski, 1975, pl. 3, figs. 3–6; Perch-Nielsen, 1975:686, pl. 3, figs. 11, 15, 16.

### Genus *Dictyocha* Ehrenberg, 1837

*Dictyocha fibula* Ehrenberg, 1839, sensu lato
Illustration: Plate 22: figures 1–9, Plate 23: figure 1.
Description: Ehrenberg, 1839:129 (fide Loeblich et al., 1968:35, 90).

Discussion: No attempt was made to subdivide this taxon. A generalized species concept was adopted in which the difference between *D. fibula* and *D. rhombica* is the orientation of the apical rod; in *D. fibula* it is parallel to the major axis of the apical ring.

*Dictyocha rhombica* (Schulz) Deflandre, 1941, sensu lato

Illustration: Plate 23: figures 2, 4, 5.

Description: Deflandre, 1941:101, figs. 1–7 (fide Loeblich et al, 1968:41, 91).

Discussion: No attempt was made to subdivide this taxon except to note the apparently new species here listed as *Dictyocha* species A and species B.

*Dictyocha* sp. A

Illustration: Plate 23: figures 3, 6–9.

Description: This species is characterized by its elongate basal ring, transverse apical rod, and the frequently double-ended basal horns in the transverse direction. As noted on Plate 23, a transition from more or less regular *D. rhombica* to a typical *Dictyocha* species A can be postulated.

*Dictyocha* sp. B

Illustration: Plate 24: figure 1.

Description: Although probably only a variant of *Dictyocha* species A, the orientation of the apical rod in the major axis requires at least temporary separation until a detailed population study can be completed.

### Genus *Distephanus* Stöhr, 1880

*Distephanus crux* (Ehrenberg) Haeckel, 1887, sensu lato

Illustration: Plate 24: figures 2–9, Plate 25: figures 1–3.

Description: Haeckel, 1887:1563.

*Distephanus speculum* (Ehrenberg) Haeckel, 1887, sensu lato

Illustration: Plate 25: figures 4–7.

Description: Haeckel, 1887:1556.

Discussion: No attempt was made to subdivide this taxon, with the exception of *D. speculum* var. *pentagonus*.

*Distephanus speculum* var. *pentagonus* Lemmermann, 1901

Illustration: Plate 25: figures 8, 9.

Description: Lemmermann, 1901:264, pl. 11: fig. 19; Ciesielski, 1975, pl. 10: figs. 4–8.

*Distephanus stauracanthus* Ehrenberg, 1845b

Illustration: Plate 26: figures 1, 2.

Description: Ehrenberg, 1845b:56, 57, 76 (fide Loeblich et al., 1968:43–44, 115–116).

Discussion: Dumitrică (1973:850–851) brought *D. Crux* var. *octacanthus* and *Dictyocha fibula* var. *octagona* into synonymy, because he found them closely associated in the Radiolarian Horizon (middle Miocene, Romania). In correlating this deposit with the Hawthorn Formation in South Carolina, we have made use of this conspecificity (Ernissee, Abbott, and Huddlestun, 1977).

### Genus *Halicalyptra* Dumitrică, 1973

*Halicalyptra picassoi* (Stradner) Dumitrică, 1973

Illustration: Plate 26: figures 3–6.

Description: Stradner, 1961; 92, figs. 101–104; Dumitrică, 1973:854–855, pl. 10, fig. 5.

Discussion: Dumitrică (1973) defined this genus and distinguished it from *Cannopilus* by the fact that the number of the lateral bars, which connect the apical apparatus to the basal ring, is greater than the number of radial horns and/or basal accessory spines. The small, nearly spherical specimens observed in this study most nearly resemble those described by Dumitrică and are, therefore, included in this taxon.

### Genus *Mesocena* Ehrenberg (1843)

*Mesocena* cf. *M. elliptica* (Ehrenberg) Ehrenberg, 1844a

Illustration: Plate 26: figures 7–10.

Description: Ehrenberg, 1844a:84 (fide Loeblich et al., 1968:54, 126–127).

Discussion: Ling (1972:177–178) discussed this taxon extensively and concluded that the taxonomy is uncertain. I have followed his

precedent and lumped together the varieties found, whether they have 2, 3, or 4 radial spines and have rounded-to-squared basal rings.

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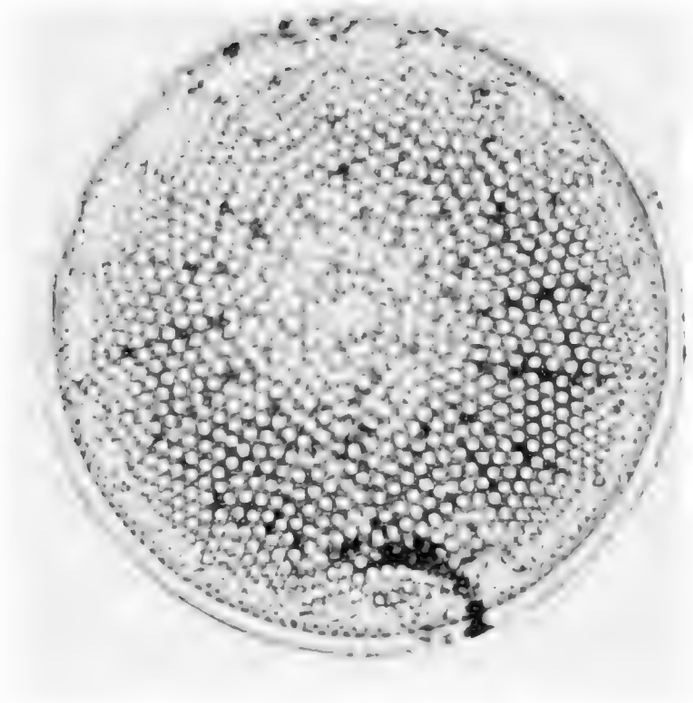
Plates 1–26



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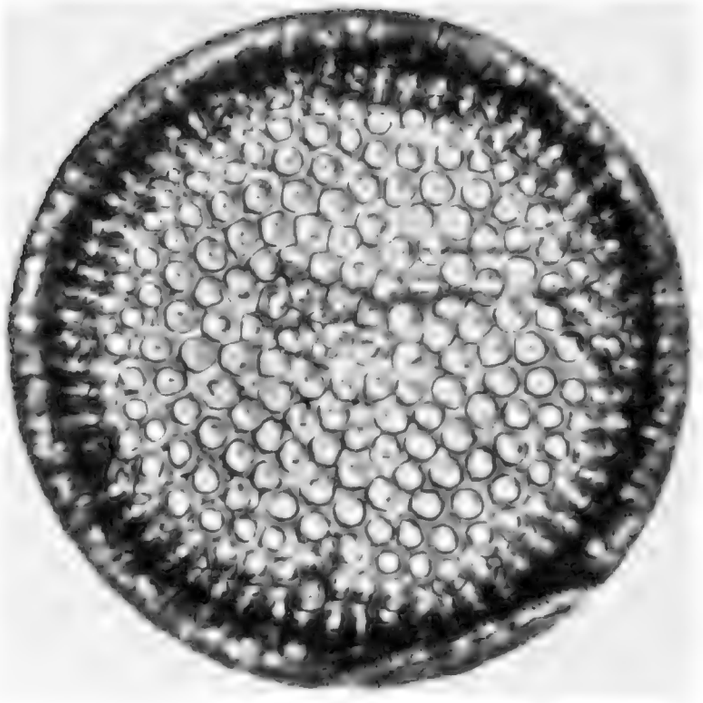

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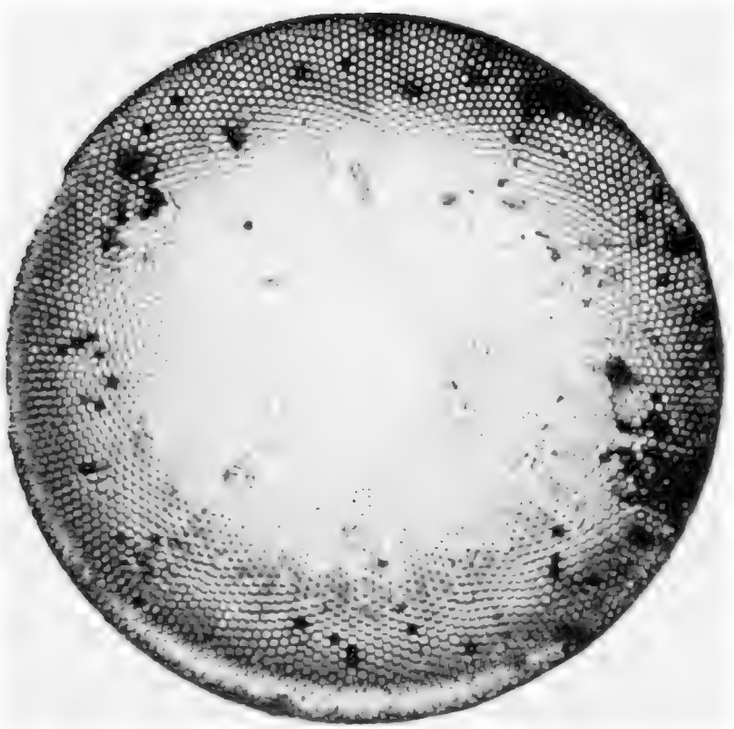

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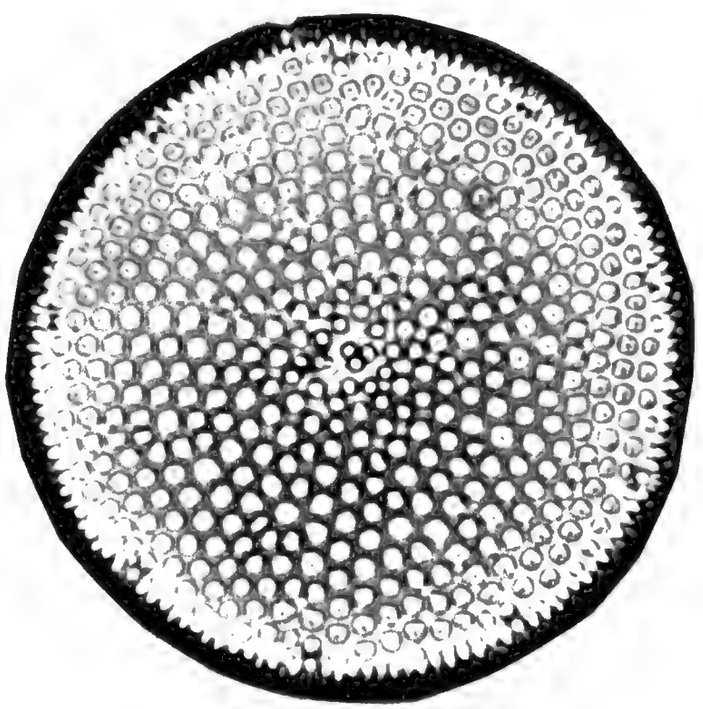

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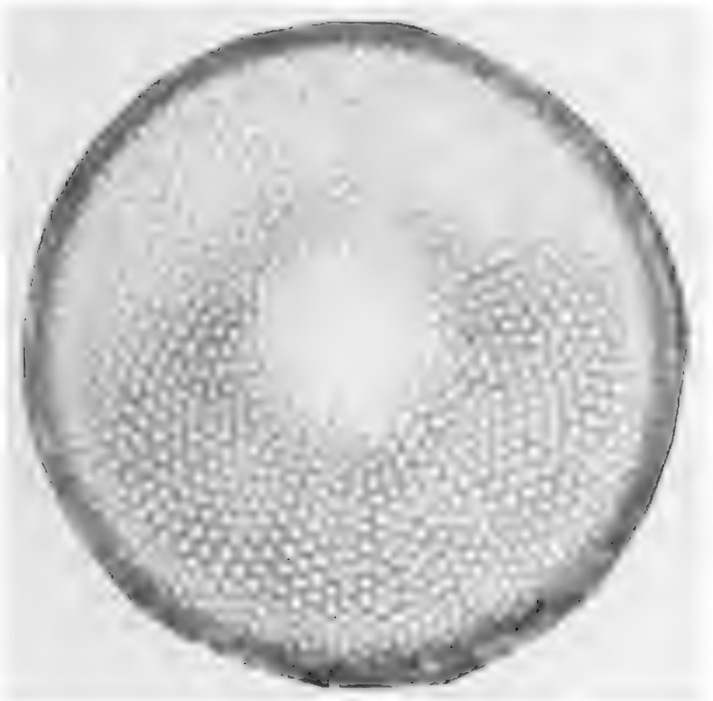
**PLATE 1**

1. *Coscinodiscus curvatulus* Grunow, diameter 41 microns, RA-13-175′.
2. *Coscinodiscus marginatus* Ehrenberg, diameter 64 microns, RA-13-163′8″
3. *Coscinodiscus gigas* var. *diorama* Grunow, diameter 234 microns, RA-13-163′8″
4. *Coscinodiscus vetustissimus* Pantocsek, diameter 24 microns, RA-13-164′8″



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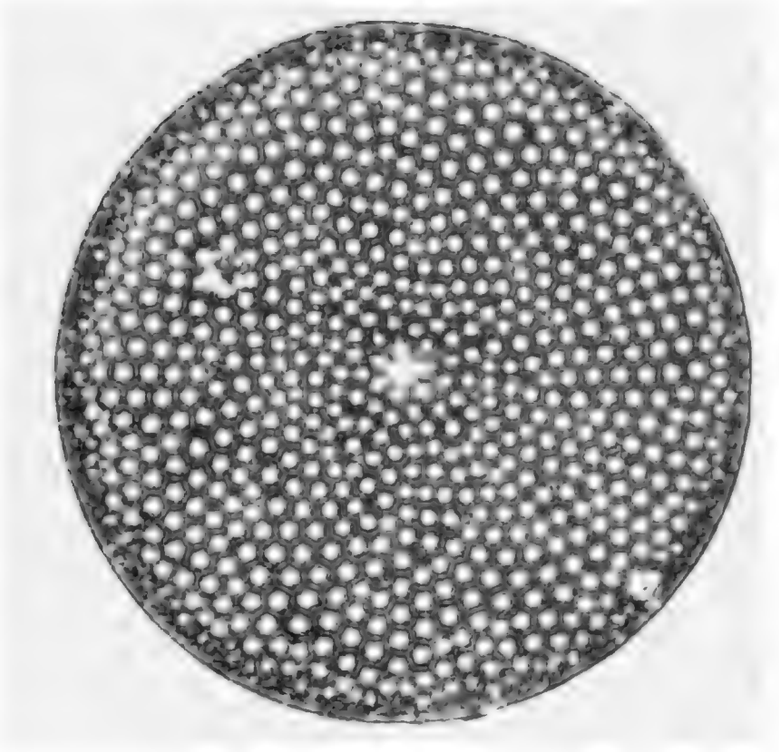

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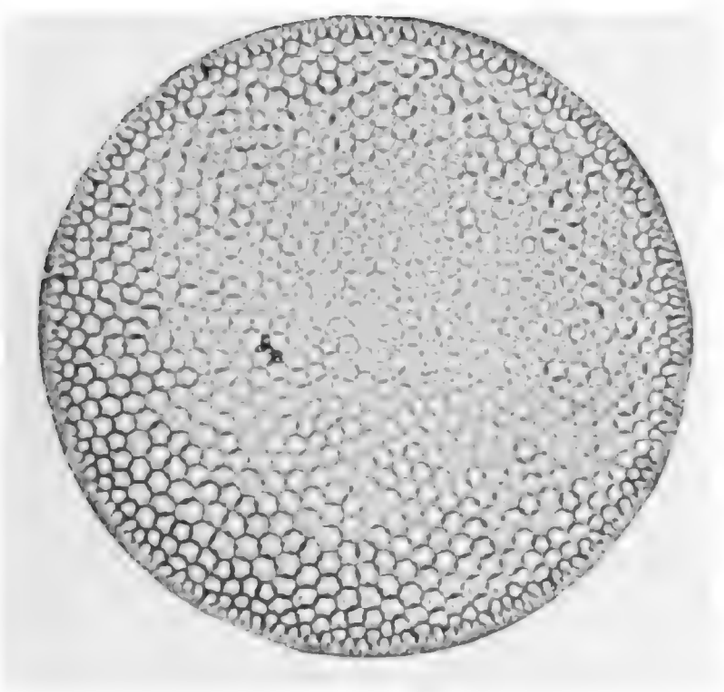

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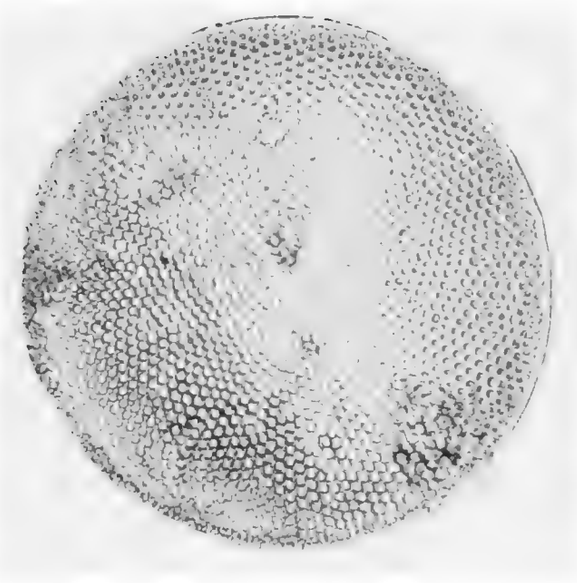

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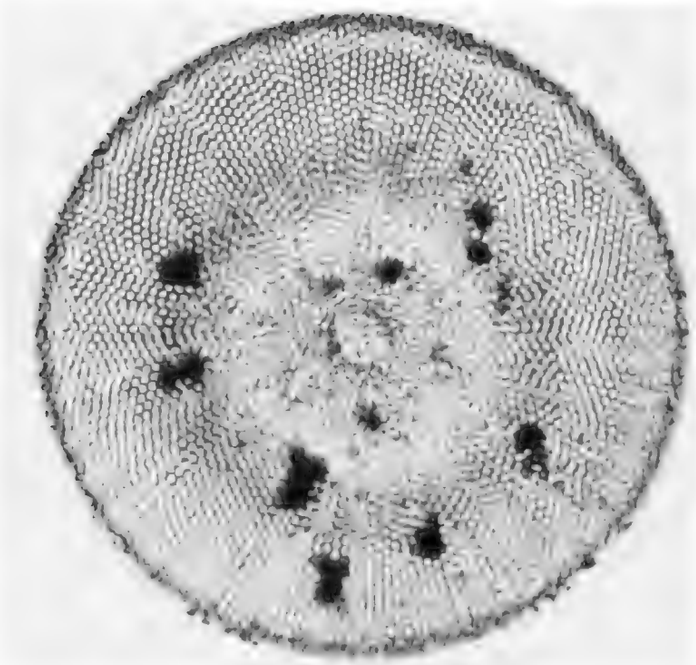
**PLATE 2**

1. *Coscinodiscus perforatus* Ehrenberg, diameter 94 microns, RA-13-163′8″
2. *Coscinodiscus perforatus* Ehrenberg, diameter 87 microns, RA-13-163′8″
3. *Coscinodiscus apiculatus* Ehrenberg, diameter 58 microns, RA-13-163′8″
4. *Coscinodiscus apiculatus* Ehrenberg, diameter 136 microns, RA-13-163′8″



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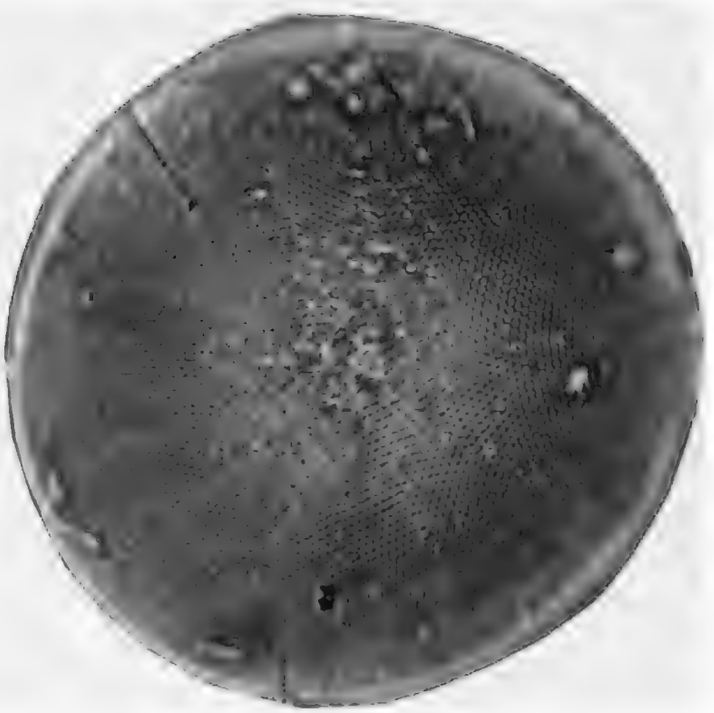

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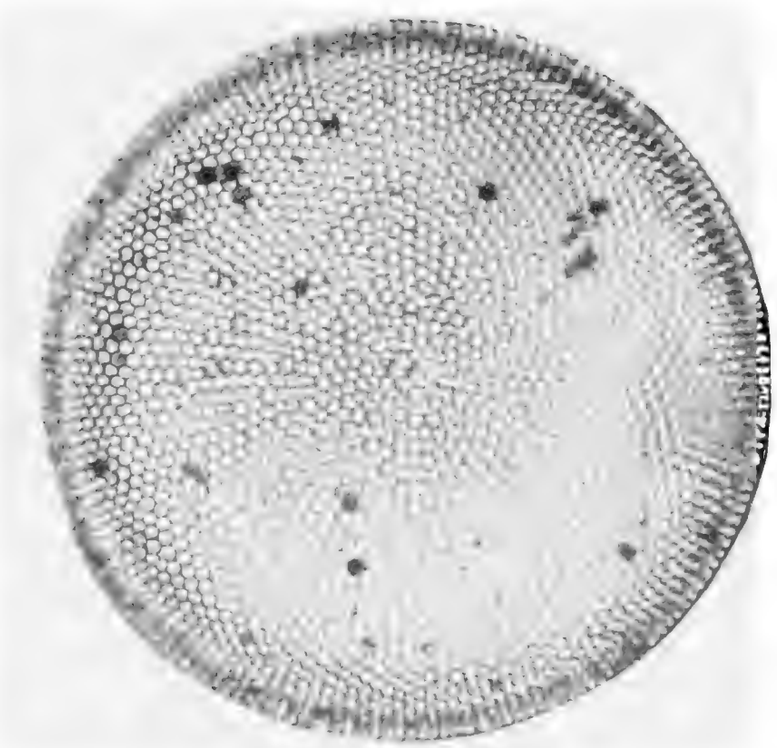

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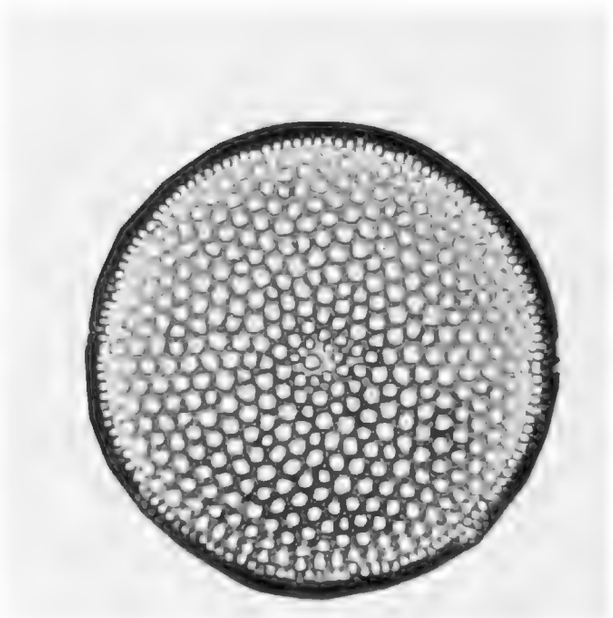

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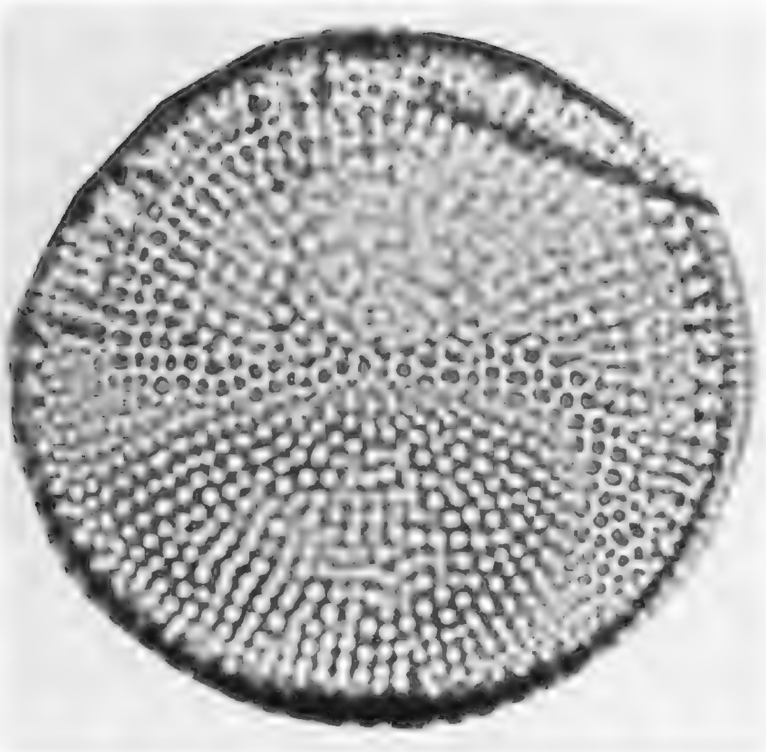
**PLATE 3**

1. *Coscinodiscus rothii* (Ehrenberg) Grunow, diameter 109 microns, RA-13-175′.
2. *Coscinodiscus stellaris* Roper, diameter 75 microns, RA-13-163′8″
3. *Coscinodiscus asteromphalus* Ehrenberg, diameter 180 microns, RA-13-163′8″
4. *Coscinodiscus nodulifer* A. Schmidt, diameter 43.5 microns, RA-13-163′8″



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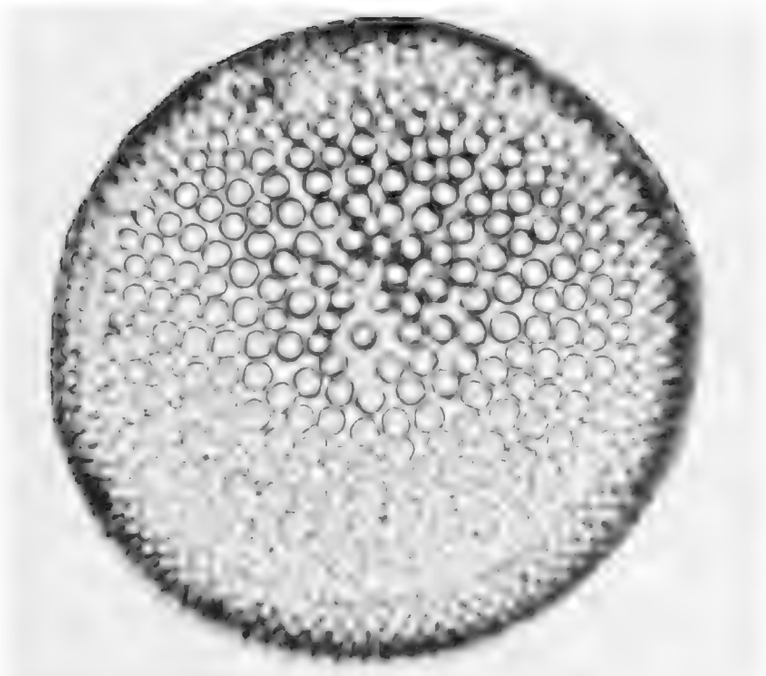

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**PLATE 4**

1. *Coscinodiscus plicatus* Grunow, diameter 32 microns, RA-13-164′8″
2. *Coscinodiscus praeyabei* Schrader, diameter 26 microns, RA-13-163′8″
3. *Actinocyclus ingens* Rattray, diameter 32 microns, RA-13-163′8″
4. *Actinocyclus ingens* Rattray, diameter 33 microns, RA-13-163′8″

## PLATE 5

1. *Paralia sulcata* (Ehrenberg) Cleve, diameter 29 microns, RA-13-164′8″.
2. *Paralia complexa* (Lohman) Andrews, diameter 19 microns, RA-13-177′9″
3. *Melosira westii* W. Smith, diameter 21 microns, RA-13-163′8″
4. *Paralia sulcata* var. *coronata* (Ehrenberg) Andrews, diameter 39 microns RA-13-175′.
5. *Hyalodiscus laevis* Ehrenberg, diameter 20 microns, RA-13-163′8″
6. *Stephanogonia actinoptychus* (Ehrenberg) Grunow, diameter 28 microns, RA-13-163′8″

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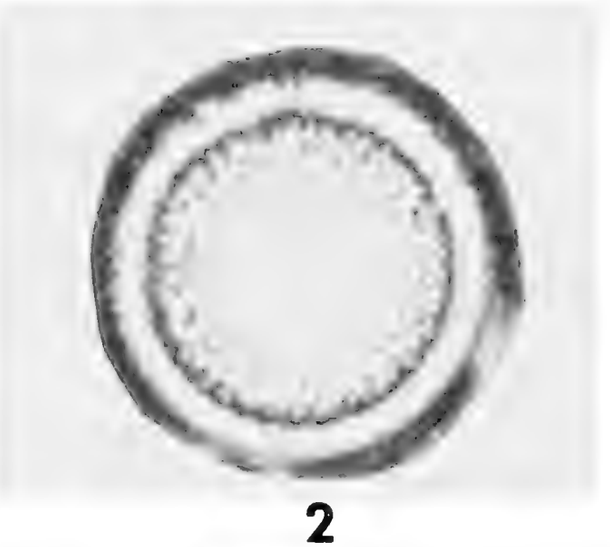

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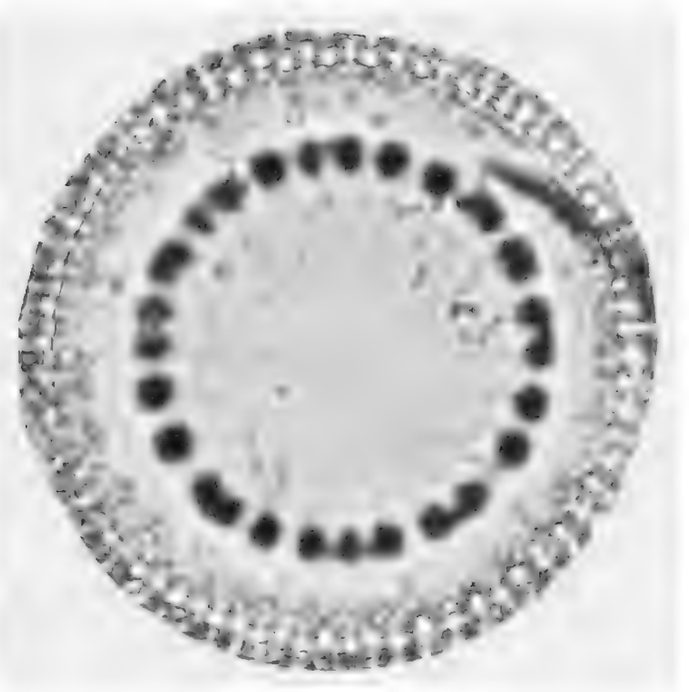

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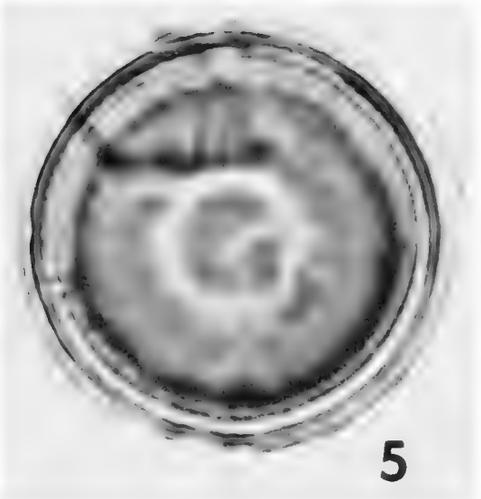

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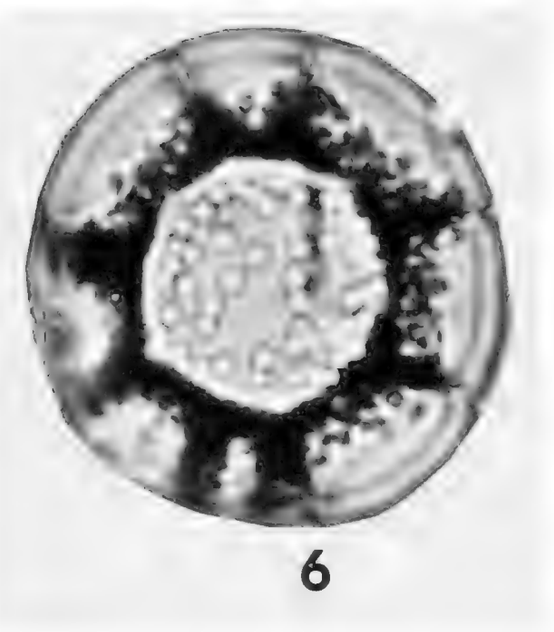

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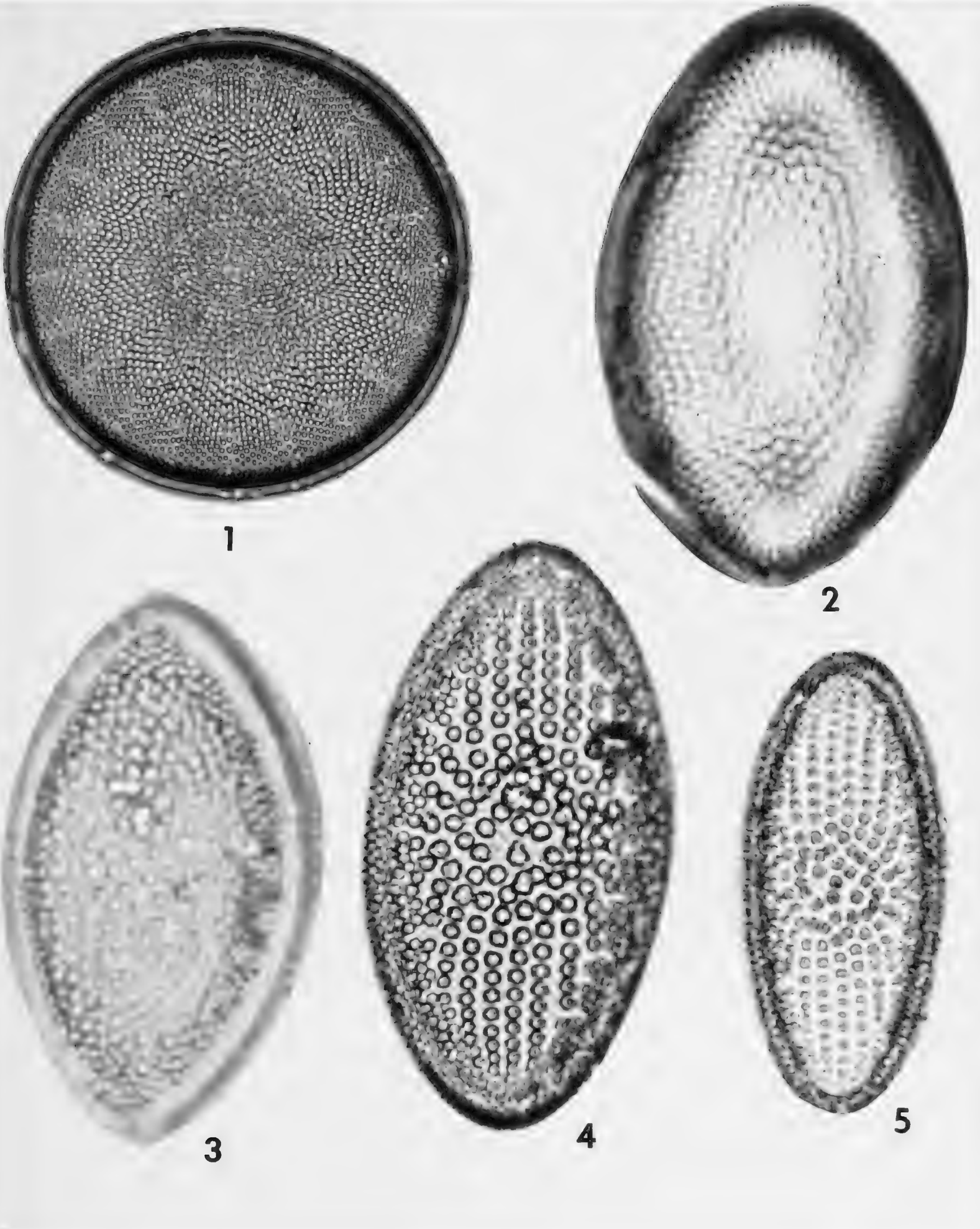
## PLATE 6

1. *Actinocyclus octonarius* Ehrenberg, diameter 97 microns, RA-13-179′.
2. *Actinocyclus ellipticus* Grunow, 34 × 22 microns, RA-13-164′8″
3. *Actinocyclus ellipticus* Grunow, 29 × 16 microns RA-13-164′8″.
4. *Coscinodiscus lewisianus* Greville, 69 × 37 microns, RA-13-164′8″
5. *Coscinodiscus lewisianus* Greville, 74 × 34 microns, RA-13-164′8″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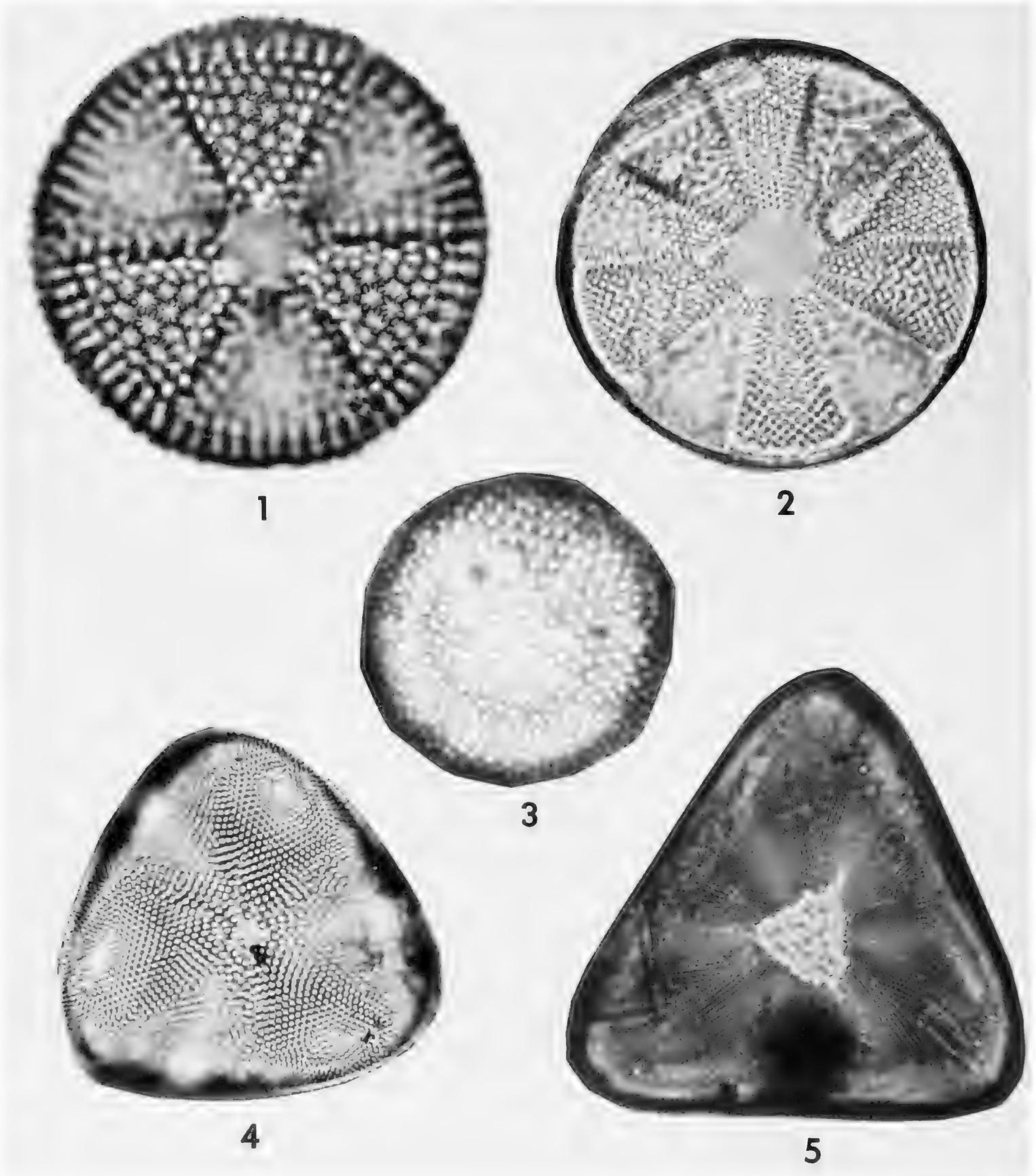



**PLATE 7**

1. *Actinoptychus senarius* Ehrenberg, diameter 66 microns, RA-13-175′.
2. *Actinoptychus virginicus* (Grunow) Andrews, diameter 38 microns, RA-13-174′.
3. *Actinocyclus tenellus* (Brébisson) Andrews, diameter 20 microns, RA-13-175′.
4. *Cymatogonia amblyoceros* Hanna, length of side 39 microns, RA-13-175′.
5. *Cymatogonia amblyoceros* Hanna, length of side 80 microns, RA-13-164′8″

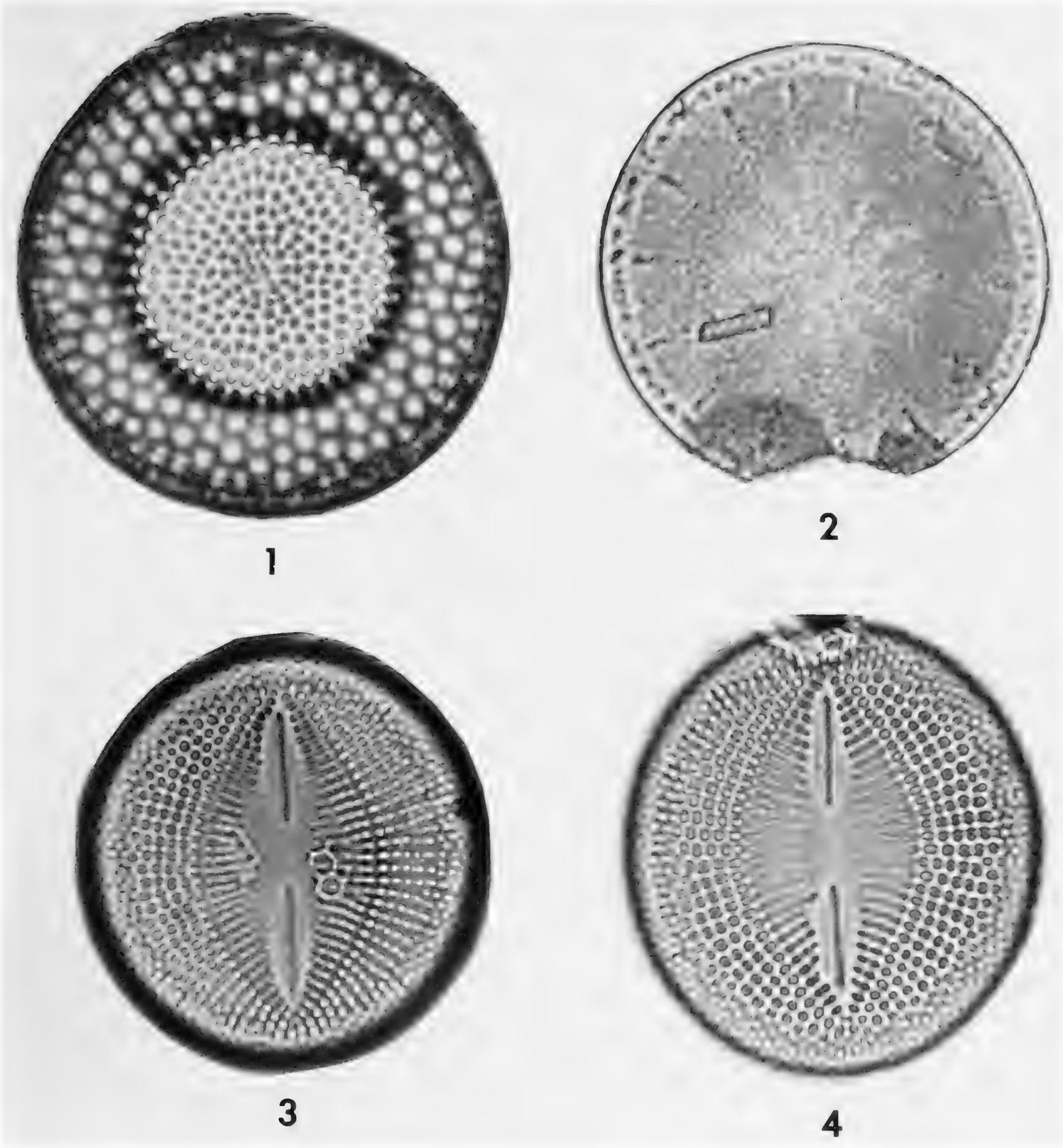



**PLATE 8**

1. *Craspedodiscus coscinodiscus* Ehrenberg, diameter 69 microns, RA-13-164′8″
2. *Cosmiodiscus elegans* Greville, diameter 58 microns, RA-13-163′8″
3. *Raphidodiscus marylandicus* Christian, diameter 27.5 microns, RA-13-175′.
4. *Raphidodiscus marylandicus* Christian, diameter 28 microns, RA-13-175′.

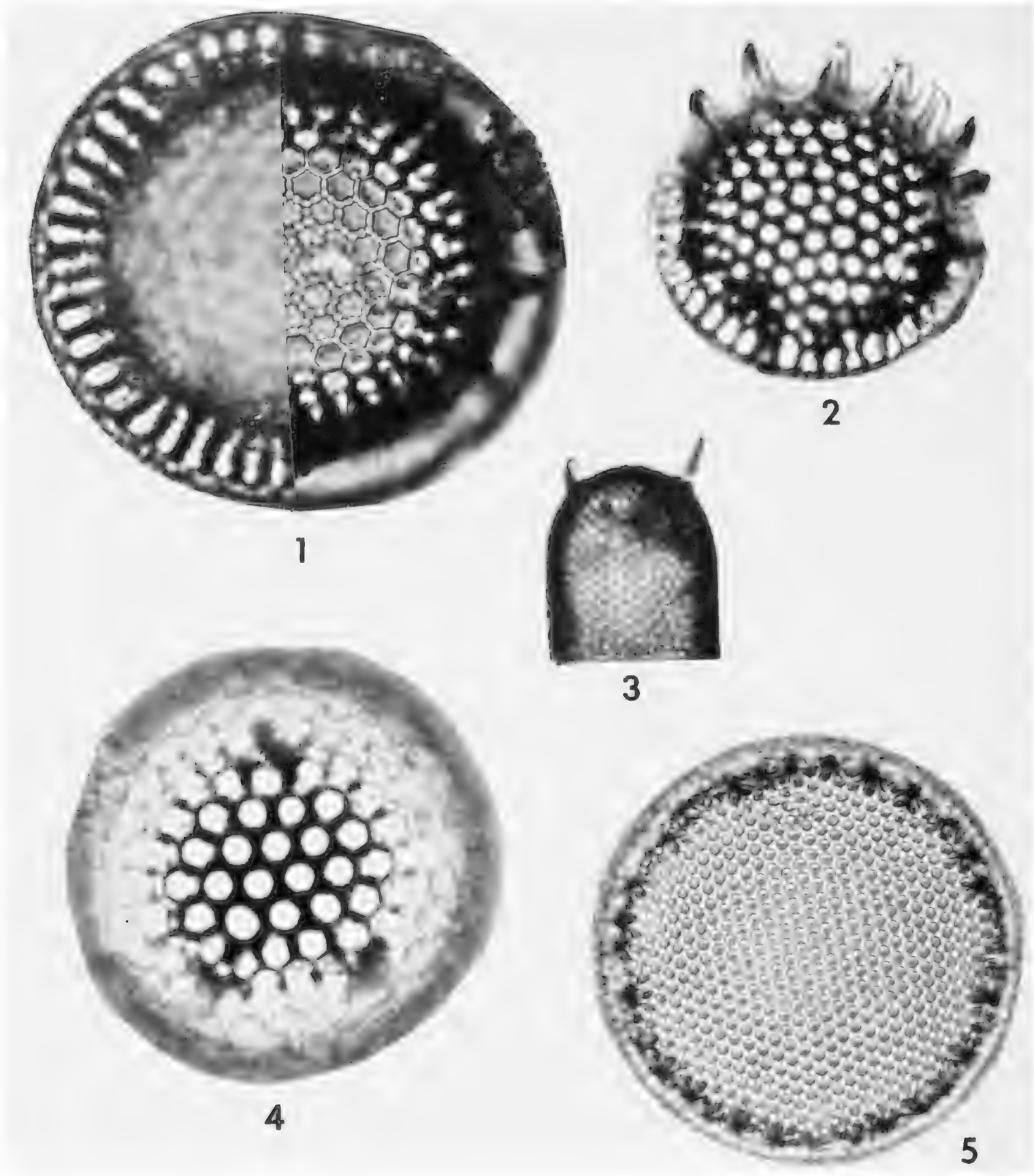



**PLATE 9**

1. *Stephanopyxis grunowii* Grove and Sturt, diameter 43 microns, RA-13-163′8″ The left of photo is focused on base of frustule and the right of photo is focused on top of frustule.
2. *Stephanopyxis grunowii* Grove and Sturt, diameter 40 microns, RA-13-163′8″
3. *Stephanopyxis turris* (Greville and Arnott) Ralfs, width 20 microns, height 24 microns RA-13-177′9″
4. *Stephanopyxis turris* (Greville and Arnott) Ralfs, diameter 32 microns, RA-13-164′8″
5. *Stephanopyxis lineata* (Ehrenberg) Forti, diameter 63 microns, RA-13-163′8″

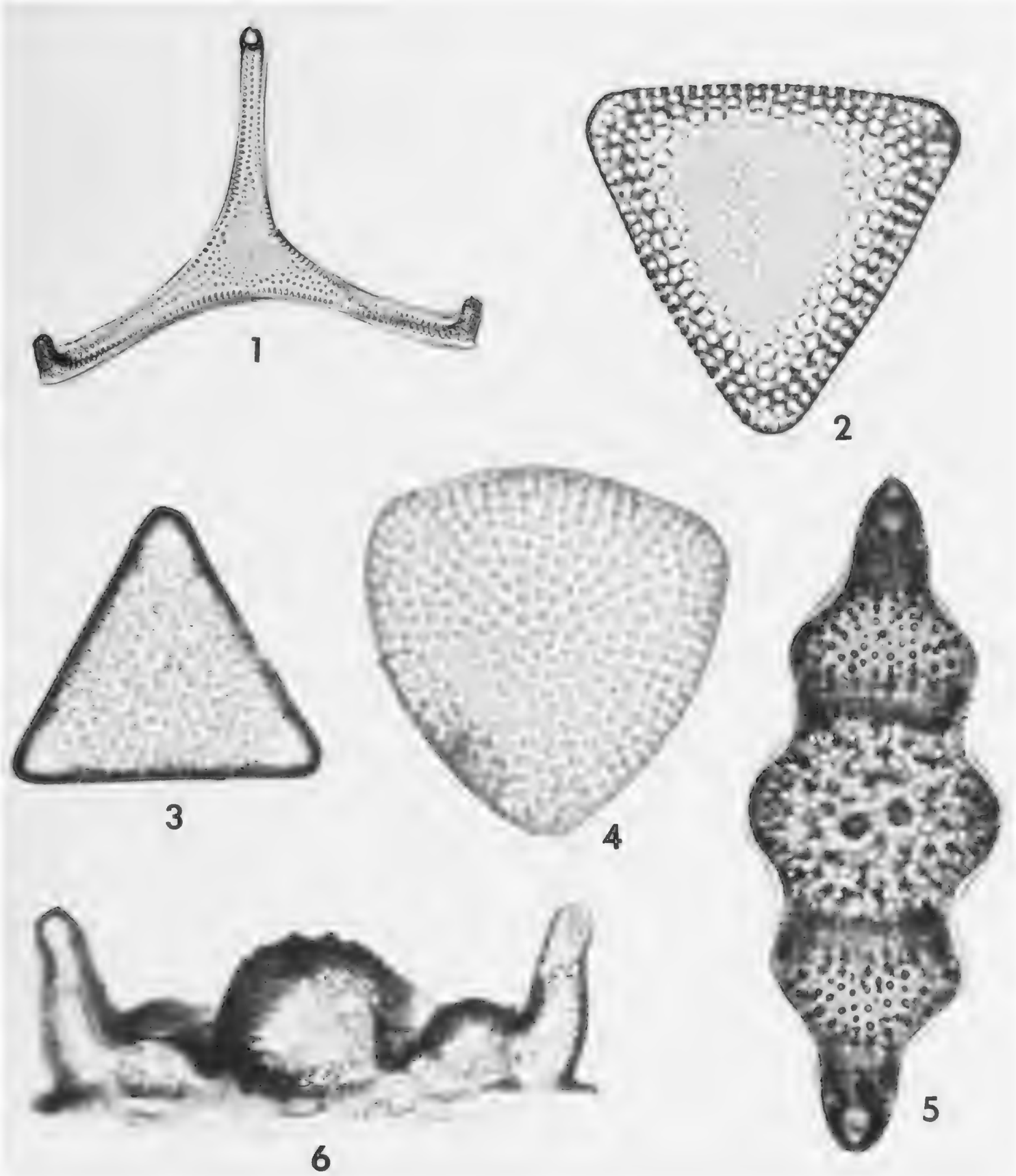
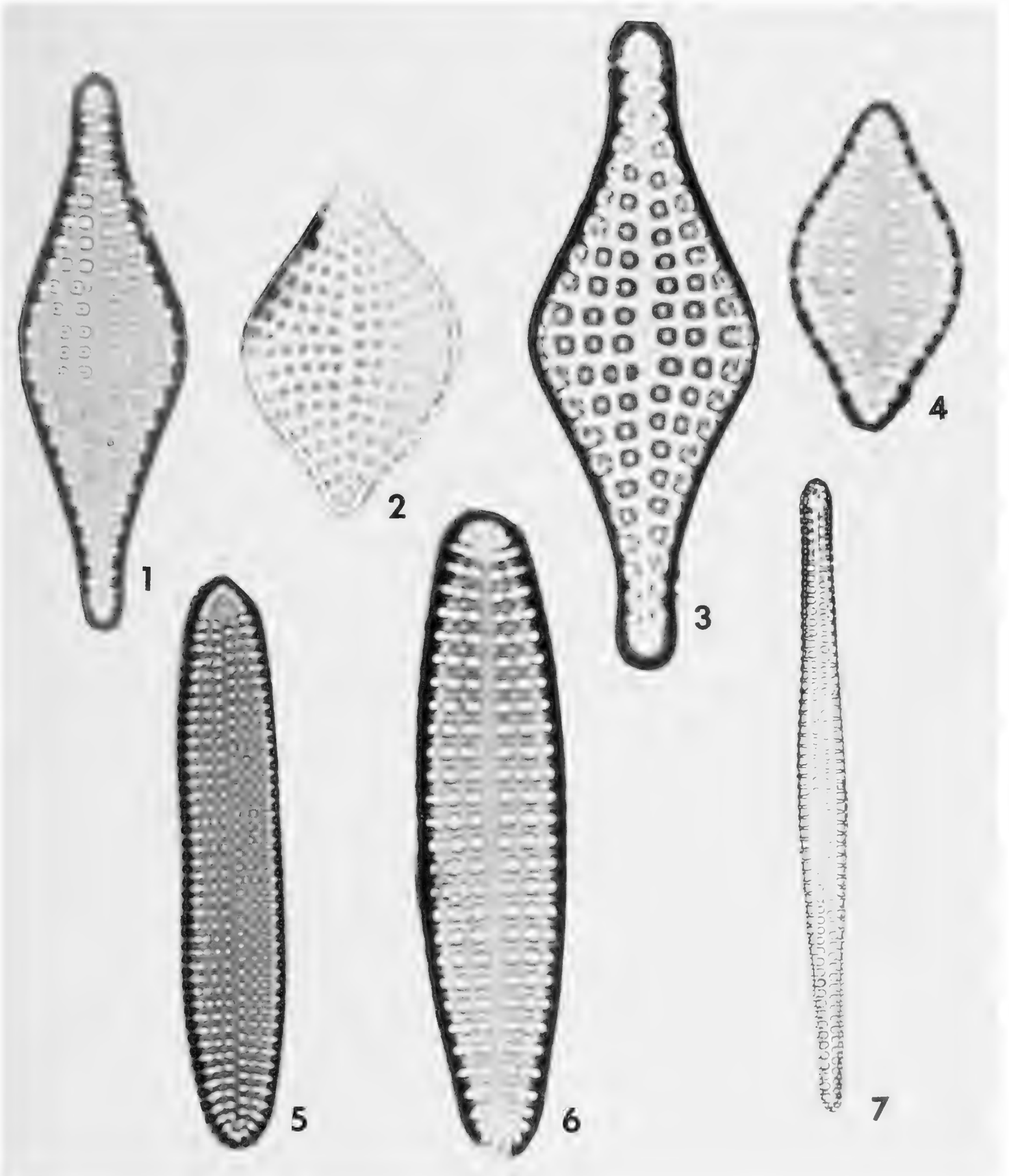



**PLATE 10**

1. *Trinacria excavata* Heiberg, length of side 59 microns, RA-13-177′9″
2. *Triceratium condecorum* Brightwell, length of side 53 microns, RA-13-179′.
3. *Triceratium tessellatum* Greville, length of side 37 microns, RA-13-179′.
4. *Triceratium subrotundatum* Schmidt, length of side 42 microns, RA-13-175′.
5. *Biddulphia toumeyii* (Bailey) Roper, length 79 microns, valve view RA-13-179′.
6. *Biddulphia toumeyii* (Bailey) Roper, length 32 microns, girdle view, RA-13-179′.

## PLATE 11

1. *Rhaphoneis gemmifera* Ehrenberg, length 55 microns, width 17 microns, RA-13-175′.
2. *Rhaphoneis rhombica* (Grunow) Andrews, length 23 microns, width 14.5 microns, RA-13-177′9″
3. *Rhaphoneis elegans* (Pantocsek and Grunow) Hanna, length 45 microns, width 16 microns, RA-13-175′.
4. *Rhaphoneis affinis* Grunow, length 19 microns, width 11 microns, RA-13-179′
5. *Pseudodimerogramma elliptica* Schrader, in Schrader and Fenner, length 46 microns, RA-13-179′.
6. *Delphineis penelliptica* Andrews, length 46 microns, width 10 microns, RA-13-163′8″
7. *Sceptroneis grandis* Abbott, new species (holotype, USNM 222870), length 199 microns, width 17 microns, RA-13-175′.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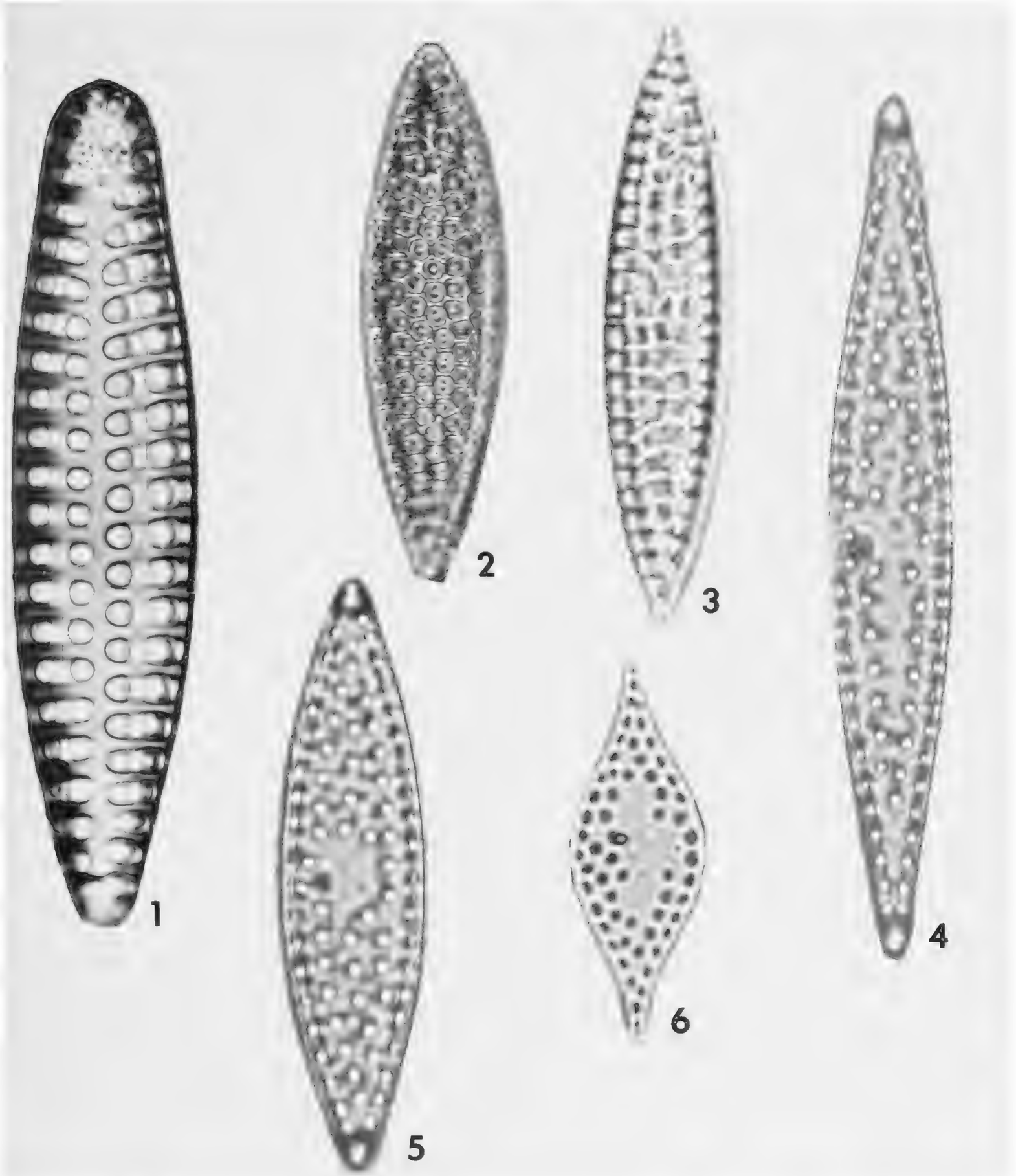
## PLATE 12

1. *Sceptroneis grandis* Abbott, new species, length 86 microns, RA-13-175′.
2. *Cussia paleacea* (Grunow) Schrader, length 50 microns, width 13 microns, RA-13-179′.
3. *Cussia praepleacea* Schrader, length 39 microns, RA-13-164′8″
4. *Cymatosira immunis* (Lohman) Abbott, new combination, length 54 microns RA-13-175′.
5. *Cymatosira andersoni* Hanna, length 37 microns, width 9 microns, RA-13-175′.
6. *Cymatosira immunis* var. A, length 22 microns, RA-13-175′.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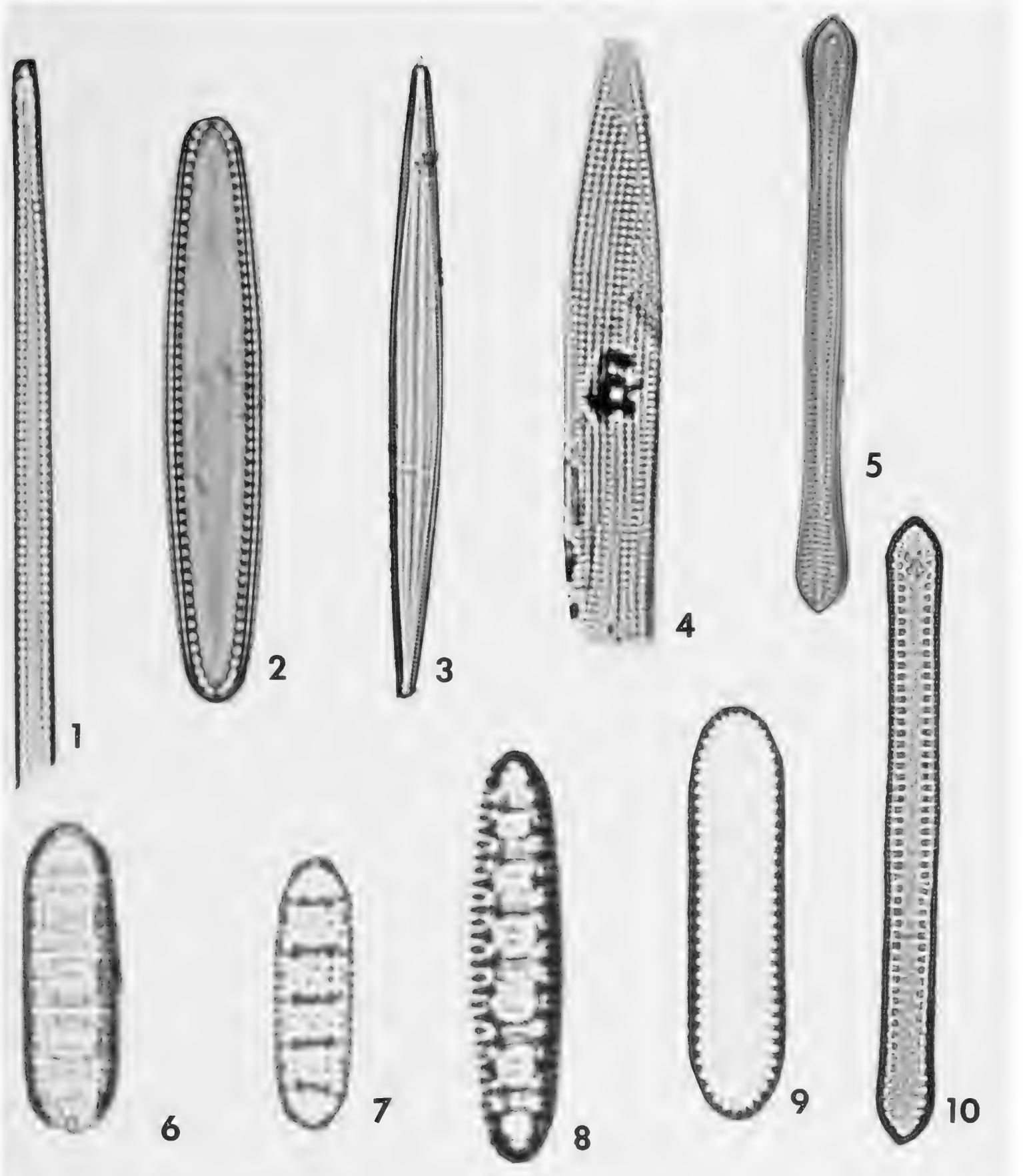
## PLATE 13

1. *Thalassiothrix longissima* Cleve and Grunow, partial specimen, RA-13-164′8″
2. *Thalassionema nitzschioides* Grunow, length 45 microns, RA-13-177′9″
3. *Synedra jouseana* Sheshukova-Poretskaya, length 95 microns, width 8 microns, RA-13-164′8″
4. *Mediaria splendida* Sheshukova-Poretskaya, length 47 microns, RA-13-179′.
5. *Clavicula polymorpha* var. *aspicephala* Pantocsek, length 110 microns, RA-13-163′8″
6. *Denticula* species, length 22 microns, RA-13-164′8″
7. *Denticula nicobarica* Grunow, length 18 microns, RA-13-164′8″
8. *Denticula hustedtii* Simonsen and Kanaya, length 27.5 microns, RA-13-163′8″
9. *Delphineis lineata* Andrews, length 39 microns, RA-13-175′.
10. *Delphineis novaecaesaraea* (Kain and Schultze) Andrews, length 75 microns, RA-13-175′.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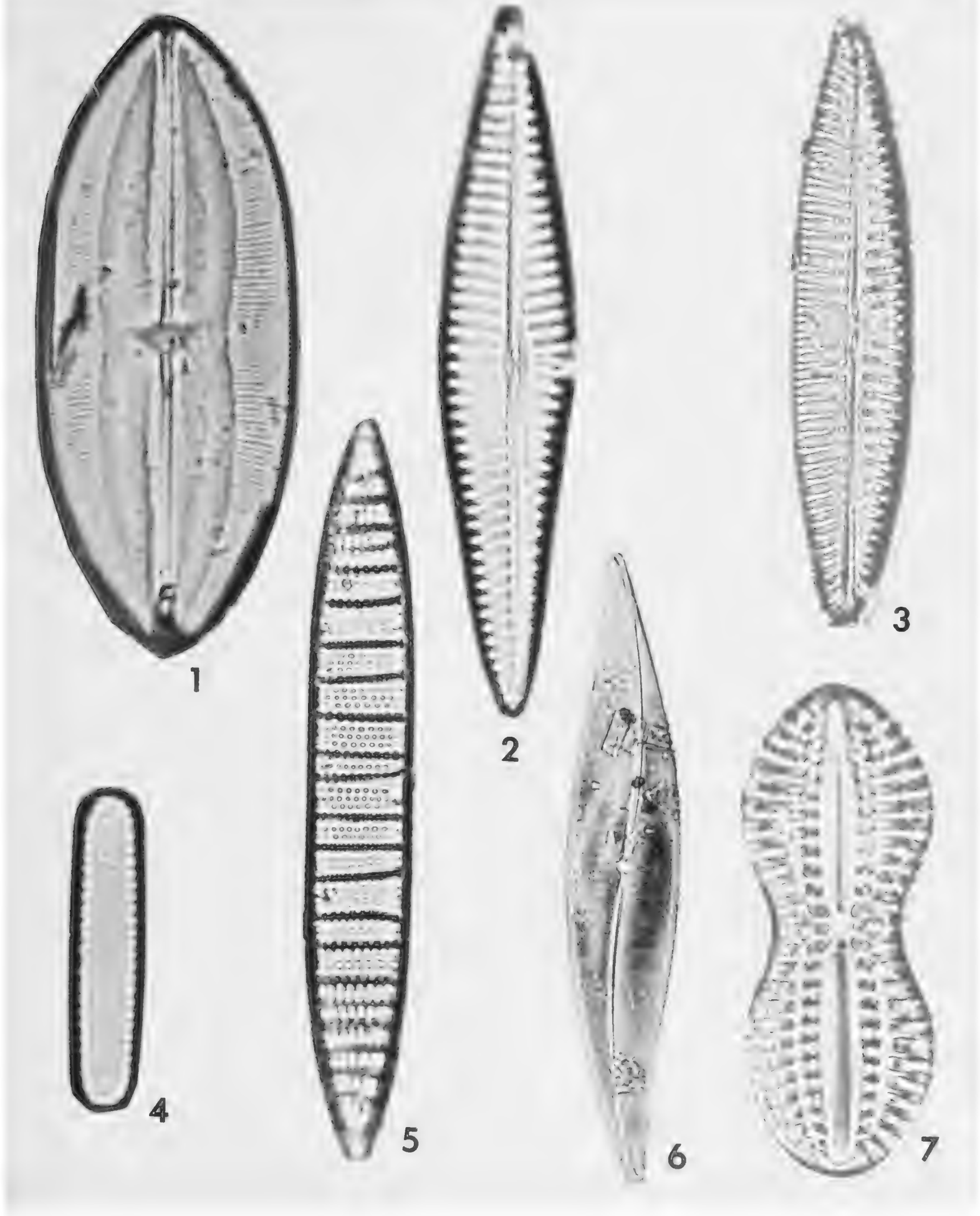
## PLATE 14

1. *Navicula hennedyii* W. Smith, length 104 microns, width 43.5 microns, RA-13-164′8″
2. *Navicula* species cf. *N. directa* Ralfs, length 51 microns, RA-13-177′9″
3. *Navicula pennata* Schmidt, length 34 microns, PA-31-205′.
4. *Nitzschia* sp. B., length 22 microns, width 4.5 microns, RA-13-176′.
5. *Denticula norwegica* Schrader, length 73 microns, width 11 microns, RA-13-179′.
6. *Pleurosigma affine* var. *marylandica* Grunow, length 168 microns, RA-13-168′.
7. *Diploneis crabro* (Ehrenberg), length 42 microns, RA-13-175′.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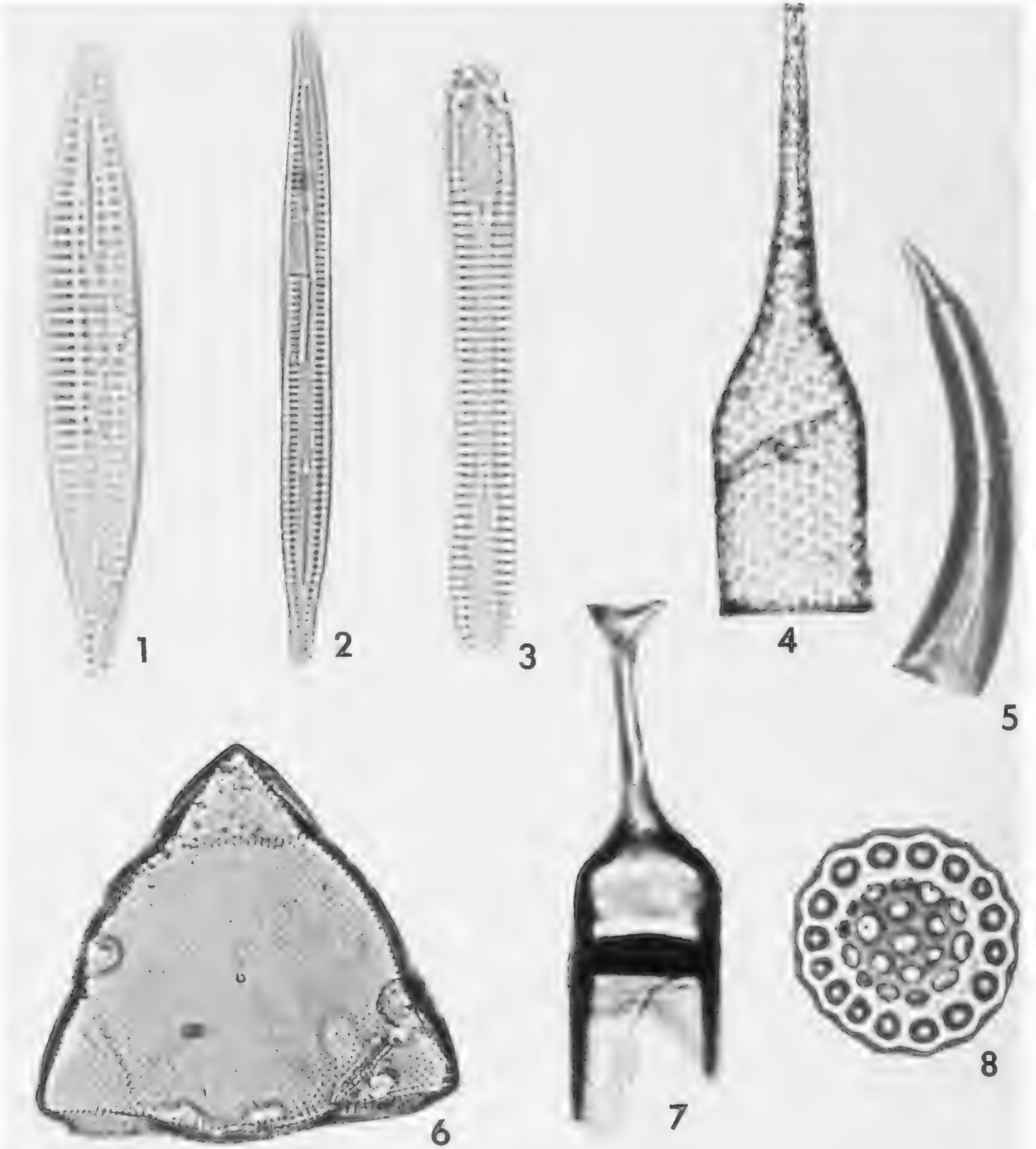



**PLATE 15**

1. *Rouxia yabei* Hanna, length 37 microns, width 7 microns, PA-31-198′.
2. *Rouxia californica* M. Peragallo, length 55 microns, RA-13-164′8″
3. *Rouxia diploneides* Schrader, approximately ×1500, RA-13-164′8″
4. *Pyxilla johnsoniana* Greville, length 69 microns, width of base 20 microns, RA-13-177′9″
5. *Rhizosolenia miocenica* Schrader, approximately ×1500, PA-31-210′.
6. *Lithodesmium minusculum* Grunow, length of side 59 microns, RA-13-163′8″
7. *Pseudopyxilla americana* (Ehrenberg) Forti, approximately ×1500, RA-13-164′8″
8. *Macrora stella* (Azpertia) Hanna, diameter 15 microns, RA-13-177′9″

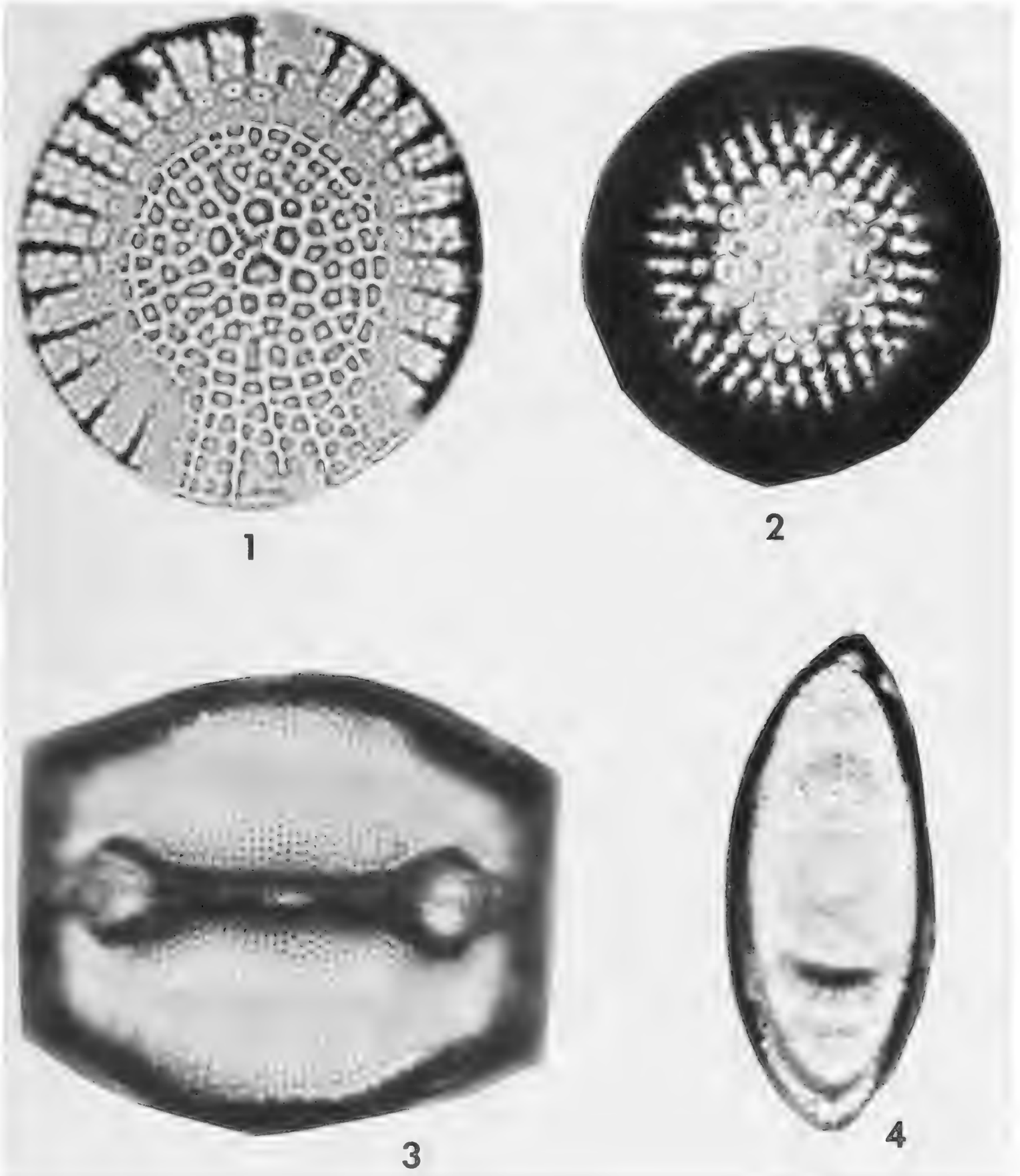



**PLATE 16**

1. *Stictodiscus kittonianus* Greville, diameter 35 microns, RA-13-163′8″
2. *Endictya robusta* Hanna and Grant, diameter 35 microns, RA-13-163′8″
3. *Goniothecium rogersii* Ehrenberg, length 47 microns, height 24 microns, girdle view, RA-13-175′.
4. *Goniothecium rogersii* Ehrenberg, length 75 microns, width 30 microns, valve view, RA-13-175′

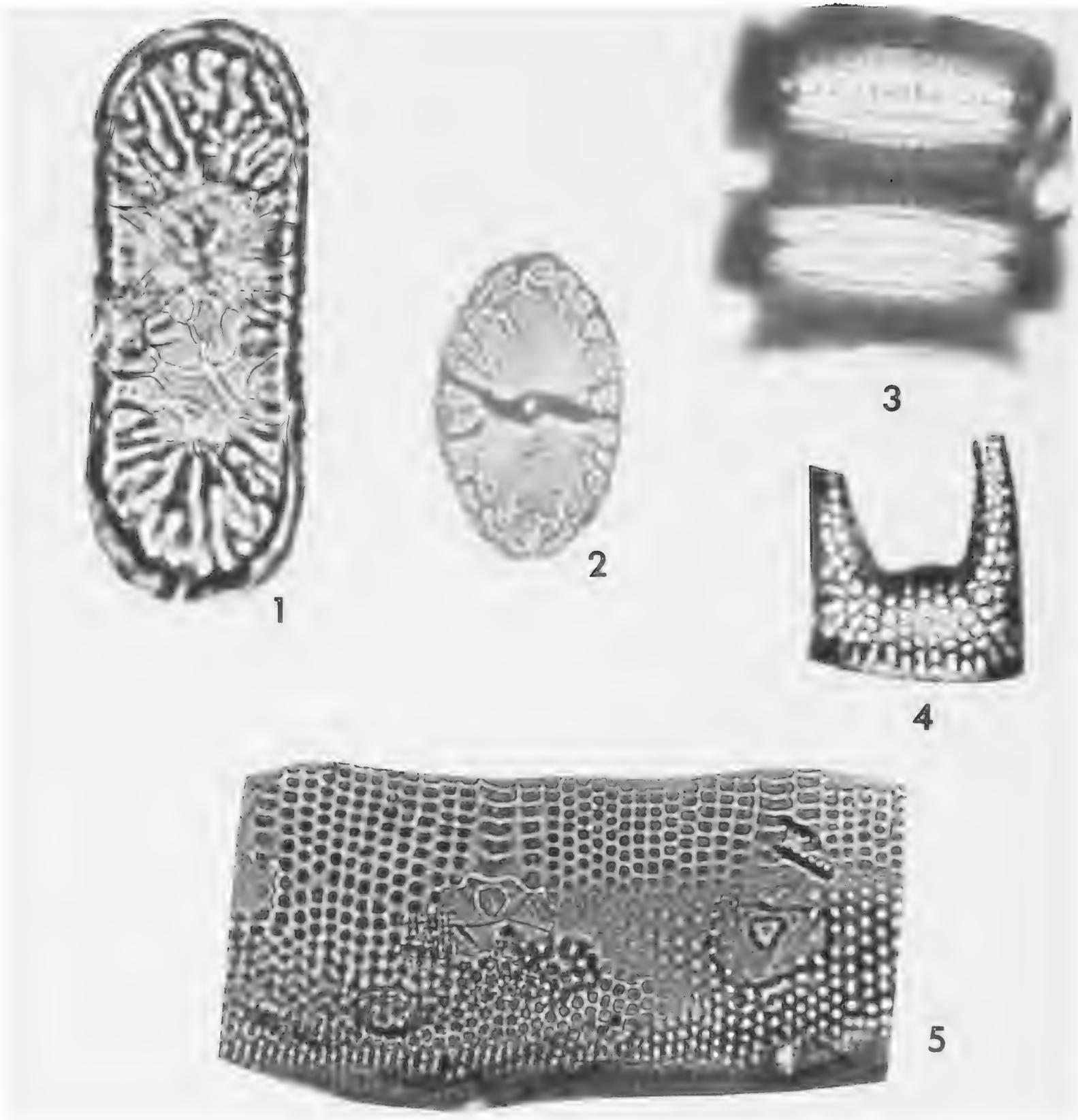



**PLATE 17**

1. *Liradiscus bipolaris* Lohman, length 49 microns, width 18 microns, RA-13-164′8″
2. *Liradiscus asperulus* Andrews, 24 × 14 microns, RA-13-177′9″
3. *Trochosira concava* Sheshukov-Poretskaya, height 12 microns, width 18 microns, RA-13-175′.
4. *Hemiaulus* cf. *polymorphus* Grunow, width 19 microns, height 22 microns, RA-13-177′.
5. *Bruniopsis mirabilis* (Brun) Karsten RA-13-163′8″

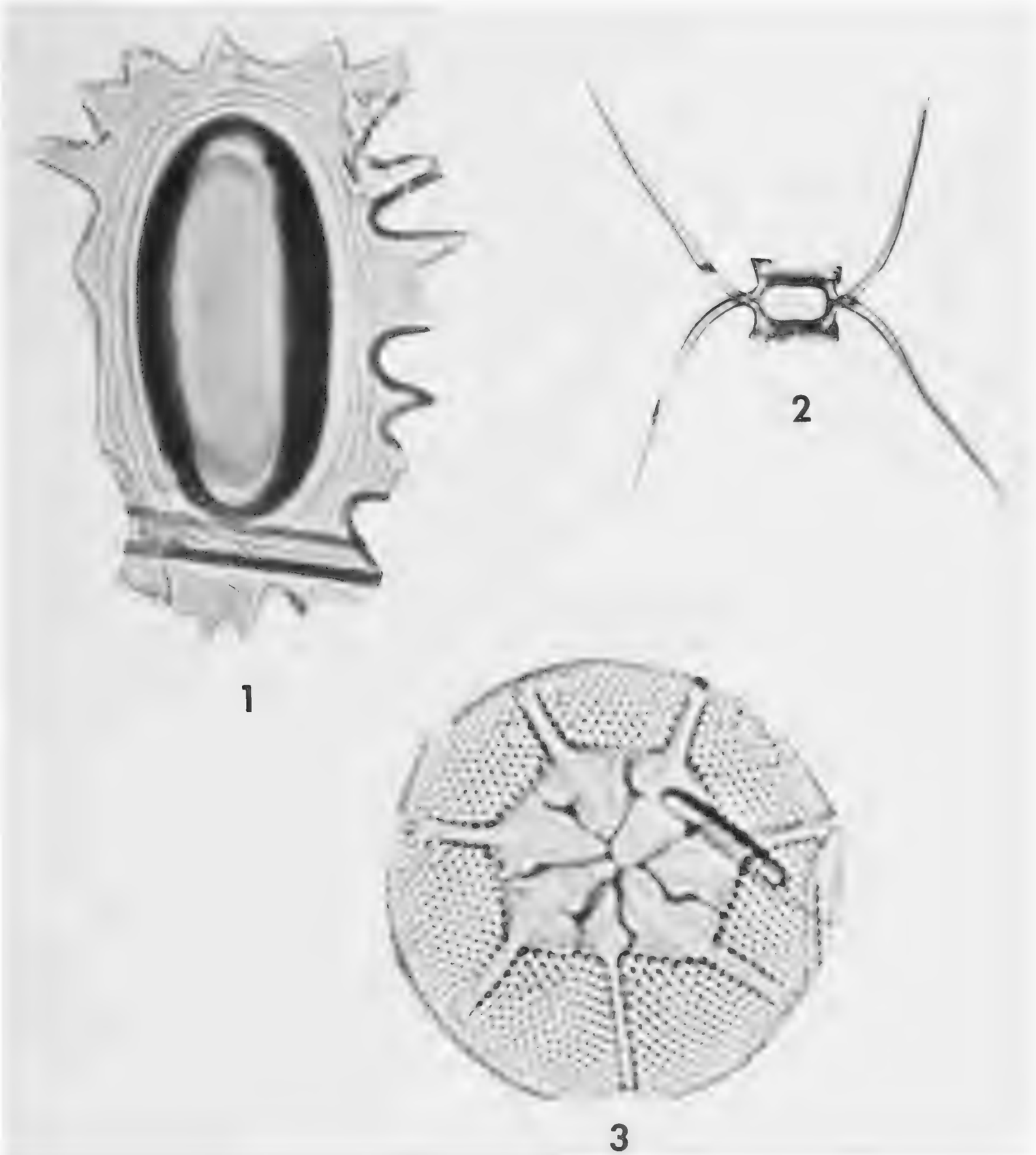


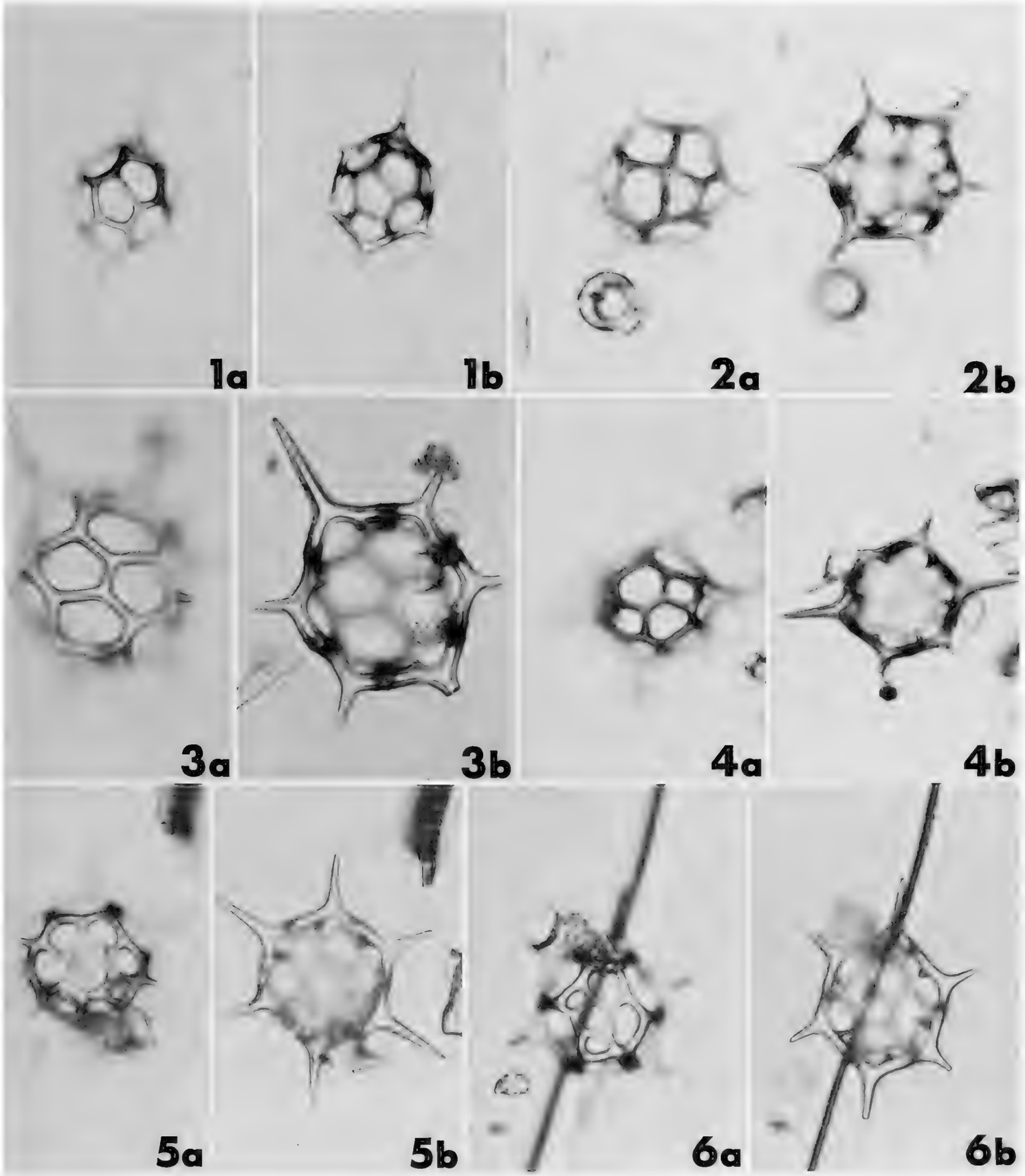

**PLATE 18**

1. *Dossetia hyalina* Andrews, length 54 microns, width 35 microns, RA-13-164′8″
2. *Chaetoceros* species, ~ ×1500, RA-13-177′9″
3. *Asteromphalus robustus* Castracane, diameter 35 microns, PA-31-205′.

## PLATE 19

1, 2. *Cannopilus binoculus* (Ehrenberg) Lemmermann: *a*, apical focus; *b*, basal ring focus; RA 13-177′9″
3, 4. *Cannopilus haeckelii* Lemmermann: *a*, apical focus; *b*, basal ring focus; RA 13-177′9″
5, 6. *Cannopilus hemisphaericus* (Ehrenberg) Haeckel: *a*, apical focus; *b*, basal ring focus; RA 13-177′9″

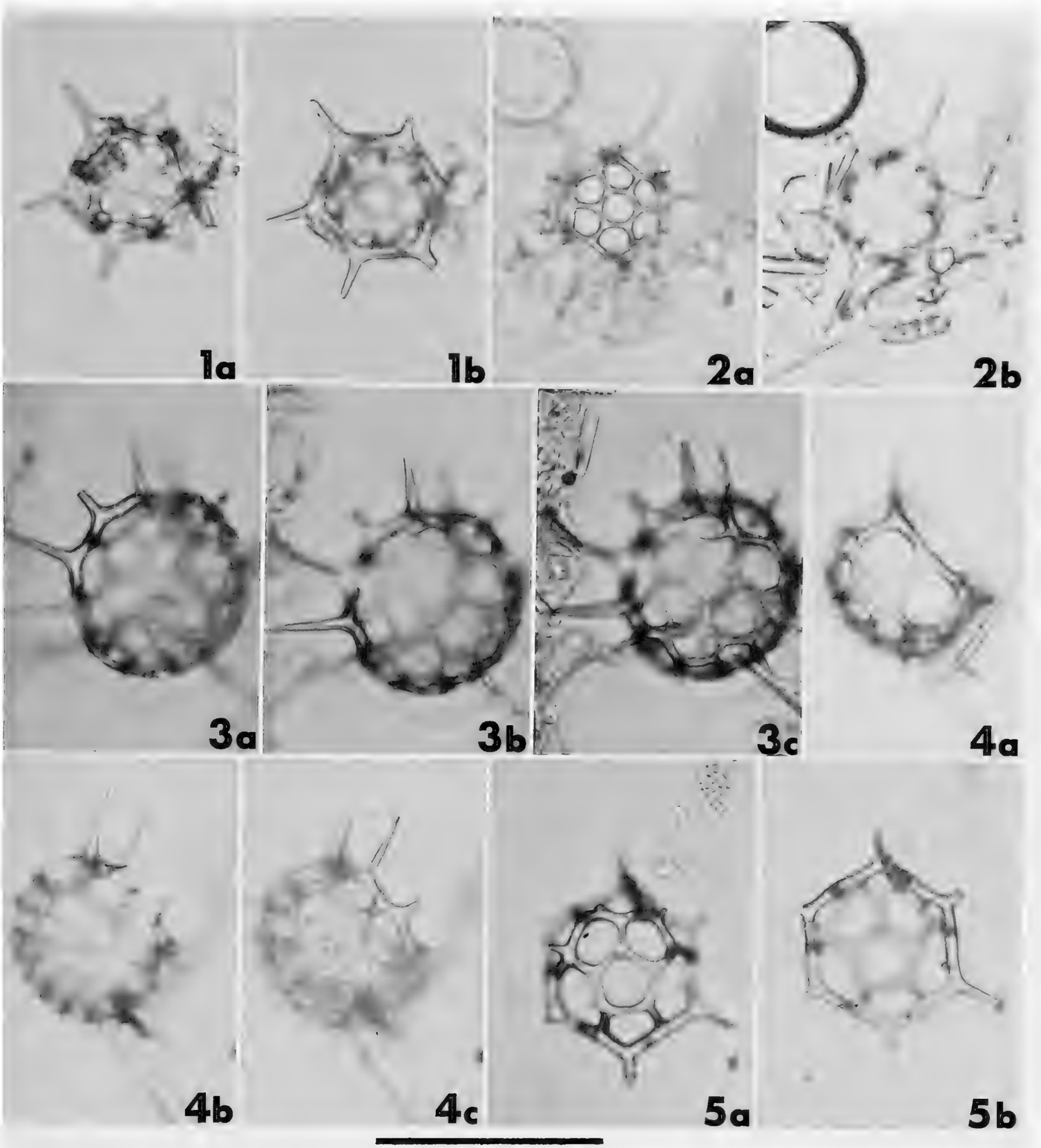
(All photographs at the same magnification; scale = 0.05 mm)


1a
1b
2a
2b
3a
3b
4a
4b
5a
5b
6a
6b

## PLATE 20

1. *Cannopilus hemisphaericus* (Ehrenberg) Haeckel: *a*, apical focus; *b* basal ring focus; RA 13-177′9″
2. *Cannopilus hemisphaericus* (Ehrenberg) Haeckel: *a*, apical focus; *b*, basal ring focus; RA 13-163′8″
3. *Cannopilus sphaericus* Gemeinhardt: *a*, low focus; *b*, mid-focus; *c*, high focus (note the large lateral windows); RA 13-163′8″
4. *Cannopilus sphaericus* Gemeinhardt: *a*, high focus; *b*, mid-focus (note accessory spines near the equatorial region of the apical apparatus); *c*, low focus (note the first row of lateral windows are larger than those remaining in the apical apparatus); RA 13-164′8″
5. *Cannopilus triommata* (Ehrenberg) Lemmermann: *a*, apical focus; *b*, basal ring focus; RA 13-163′8″

(All photographs at the same magnification, scale = 0.05 mm)

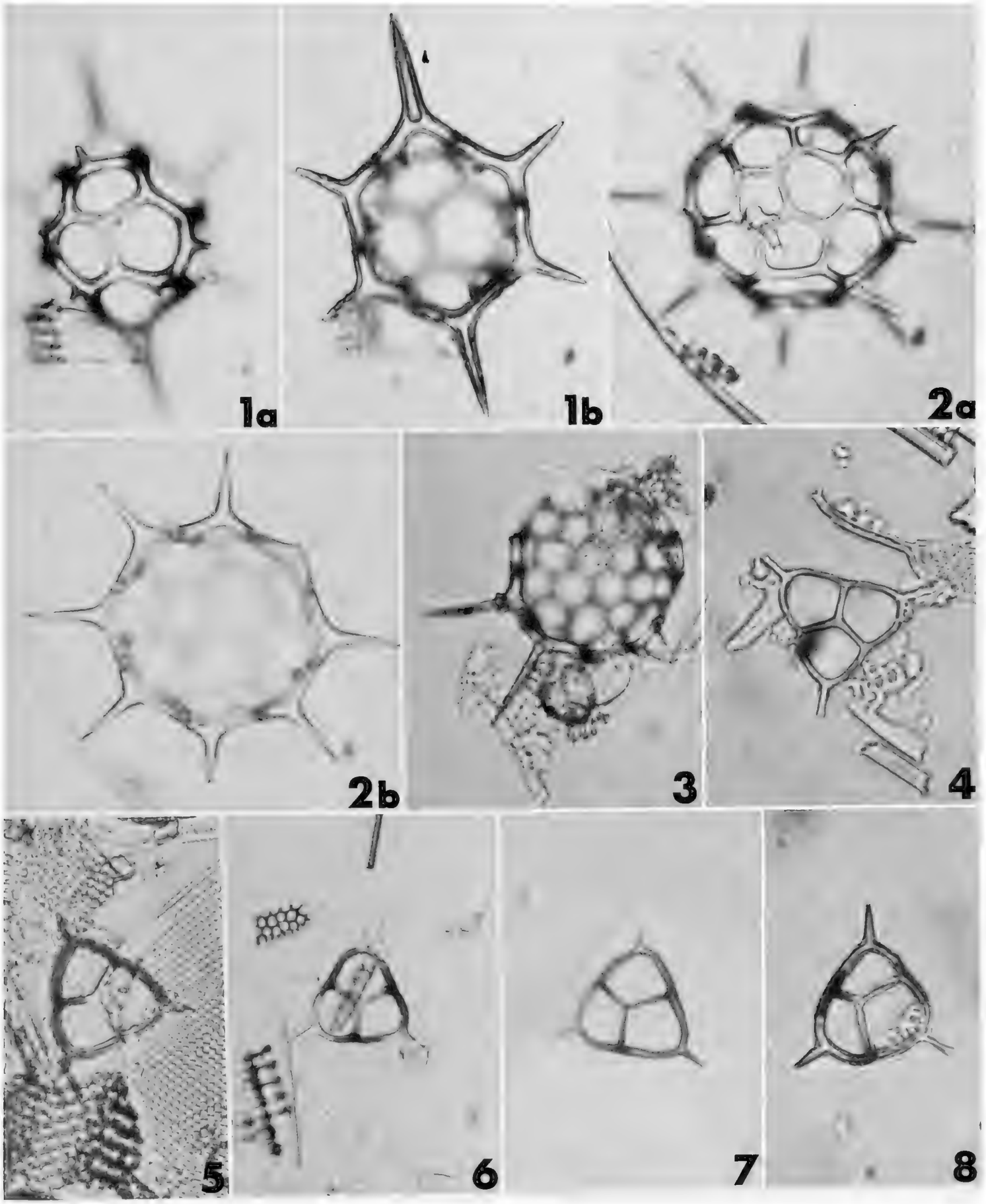

1a
1b
2a
2b
3a
3b
3c
4a
4b
4c
5a
5b

## PLATE 21

1. *Cannopilus triommata* (Ehrenberg) Lemmermann: *a*, apical focus; *b* basal ring focus; RA 13-177′9″
2. *Cannopilus* species A: *a*, apical focus; *b*, basal ring focus; RA 13-176′.
3. *Cannopilus* species B, RA 13-163′8″

4–8. *Corbisema triacantha* (Ehrenberg) Hanna: 4, PA 31-198′2″; 5, PA 31-198′2″; 6, 7, RA 13-163′8″; 8, RA 13-177′9″

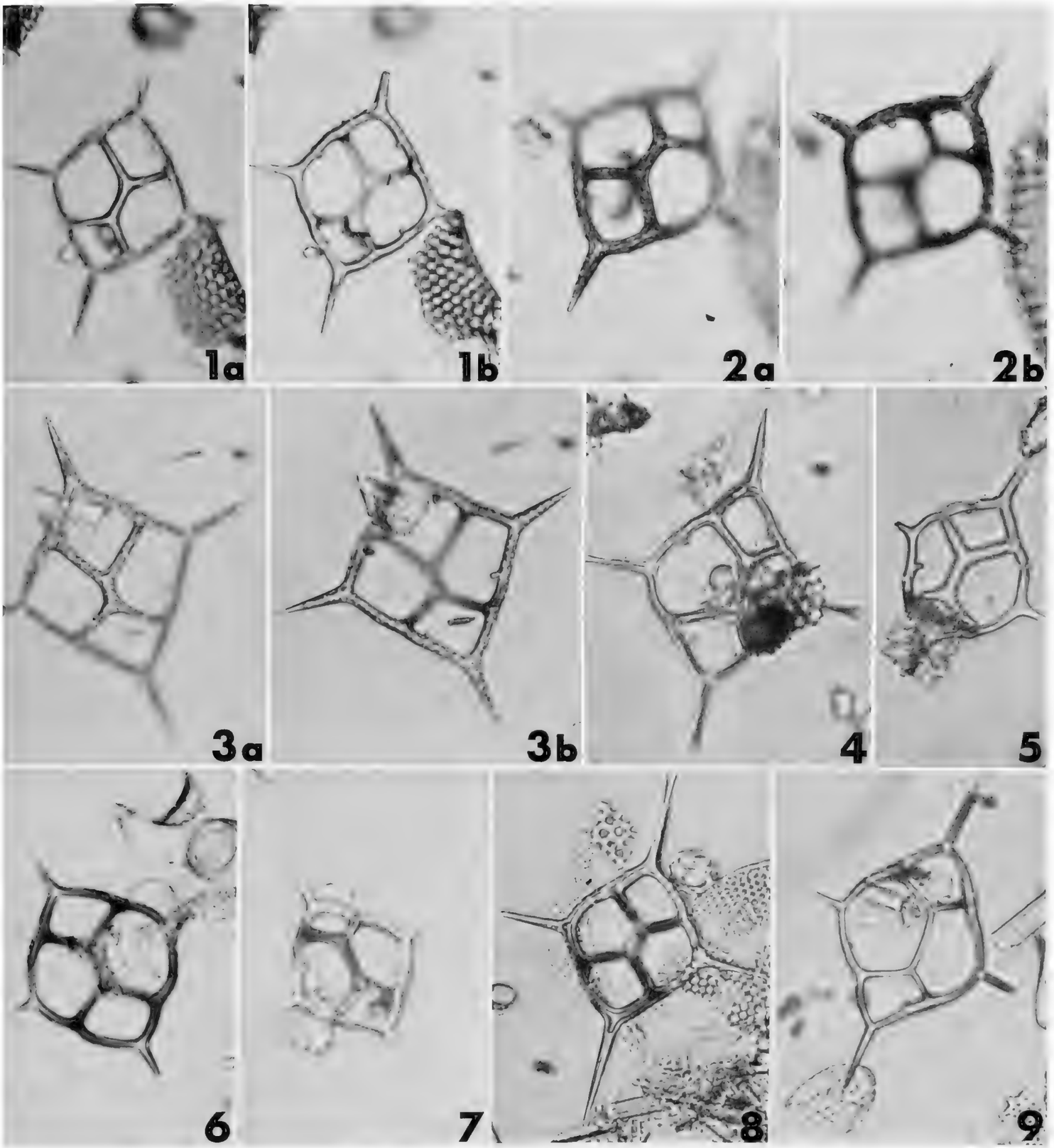
(All photographs at the same magnification, scale = 0.05 mm)


1a
1b
2a
2b
3
4
5
6
7
8

## PLATE 22

1–3. *Dictyocha fibula* Ehrenberg, sensu lato: *a*, apical focus; *b*, basal ring focus; RA 13-177′9″
4–9. *Dictyocha fibula* Ehrenberg, sensu lato: 4–7, 9, RA 13-177′9″; 8, RA 13-164′8″

(All photographs at the same magnification, scale = 0.05 mm)

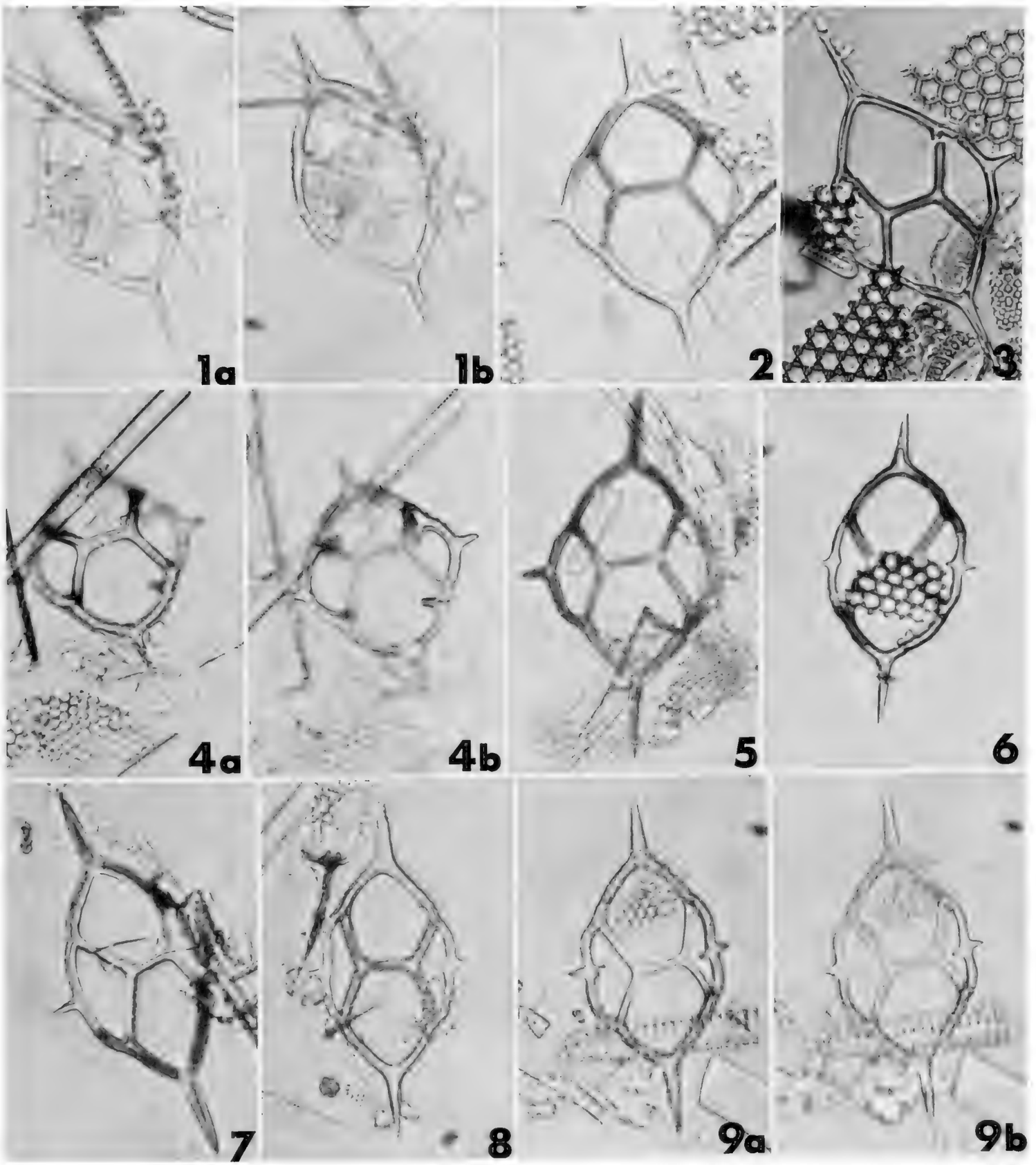

1a
1b
2a
2b
3a
3b
4
5
6
7
8
9

## PLATE 23

1. *Dictyocha fibula* Ehrenberg, sensu lato: *a*, apical focus; *b*, basal ring focus; PA 31-198′2″
2, 5. *Dictyocha rhombica* (Schultz) Deflandre, sensu lato, PA 31-198′2″
3. *Dictyocha* cf. *Dictyocha* species A, PA 31-205′4″
4. *Dictyocha rhombica* (Schultz) Deflandre, sensu lato: *a*, apical focus; *b*, basal ring focus; RA 13-164′8″
6–8. *Dictyocha* species A: 6, PA 31-205′4″; 7, 8, PA 31-198′2″
9. *Dictyocha* species A: *a*, apical focus; *b*, basal ring focus; PA 31-198′2″

Note that figure 7 does not have the double-ended basal horns that show up well in figures 6, 8, and 9. A transitional morphologic series can be postulated from figure 4 through figures 2, 5, 3, 7, 8.

(All photographs at the same magnification; scale = 0.05 mm)


1a
1b
2
3
4a
4b
5
6
7
8
9a
9b

## PLATE 24

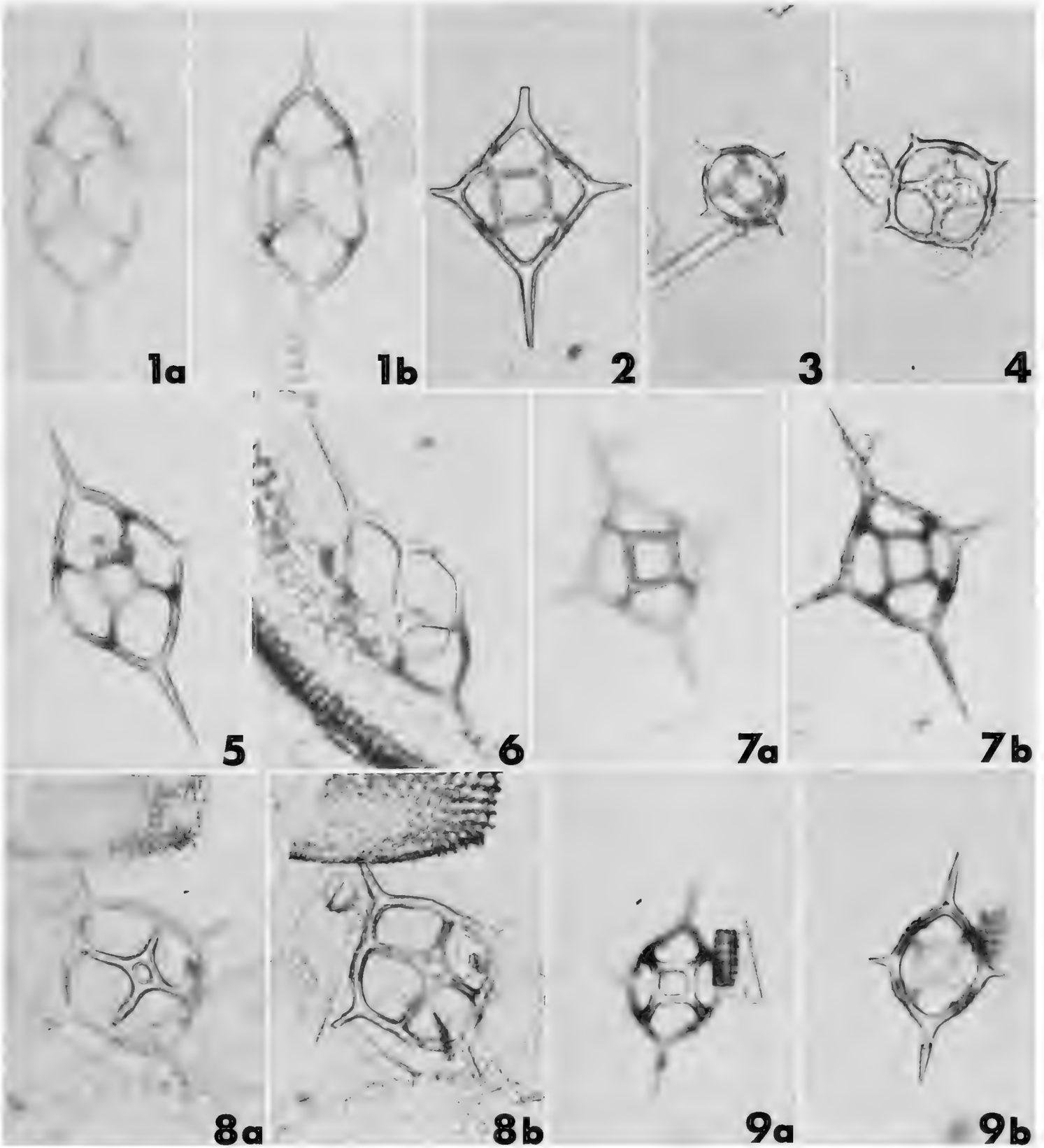
1. *Dictyocha* species B: *a*, apical focus; *b*, basal ring focus; PA 31-198′2″ This specimen shows a more pronounced elongation of the basal ring and a more severe straightening of the lateral segments of the basal ring (cf. Plate 23: figures 1, 7).

2–6. *Distephanus crux* (Ehrenberg) Haeckel, sensu lato: 2, RA 13-177′9″; 3, PA 31-198′2″; 4, RA 13-164′8″; 5, PA 31-205′4″; 6, PA 31-198′2″

7, 9. *Distephanus crux* (Ehrenberg) Haeckel, sensu lato: *a*, apical focus; *b*, basal ring focus; RA 13-177′9″. Note the surface ornamentation in figure 7.

8. *Distephanus crux* (Ehrenberg) Haeckel, sensu lato: *a*, apical focus; *b*, basal ring focus; RA 13-164′8″

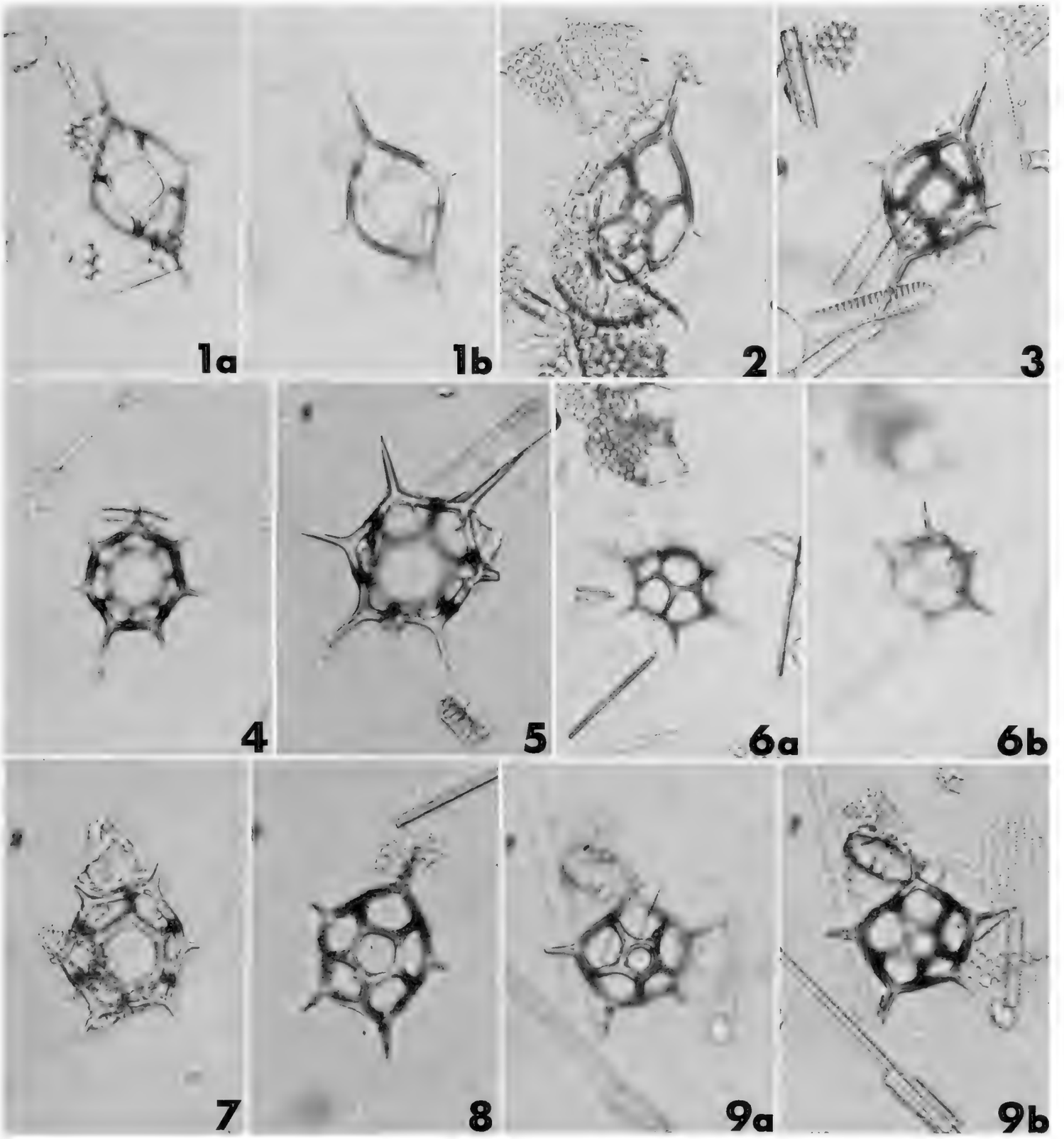
(All photographs at the same magnification, scale = 0.05 mm)


1a
1b
2
3
4
5
6
7a
7b
8a
8b
9a
9b

## PLATE 25

1. *Distephanus crux* (Ehrenberg) Haeckel, sensu lato: *a*, apical focus; *b*, basal ring focus; PA 31-198′2″
2, 3. *Distephanus crux* (Ehrenerg) Haeckel, sensu lato, PA 31-198′2″
4, 5, 7. *Distephanus speculum* (Ehrenberg) Haeckel, sensu lato: 4, 5, RA 13-163′8″; 7, PA 31-198′2″ Note 7-sided basal ring in figure 4.
6. *Distephanus speculum* (Ehrenberg) Haeckel, sensu lato: *a*, apical focus (specimen tilted); *b*, basal ring focus; RA 13-163′8″
8. *Distephanus speculum* var. *pentagonus* Lemmermann, RA 13-163′8″
9. *Distephanus speculum* var. *pentagonus* Lemmermann: *a*, apical focus; *b*, basal ring focus; RA 13-163′8″

(All photographs at the same magnification, scale = 0.05 mm)


1a
1b
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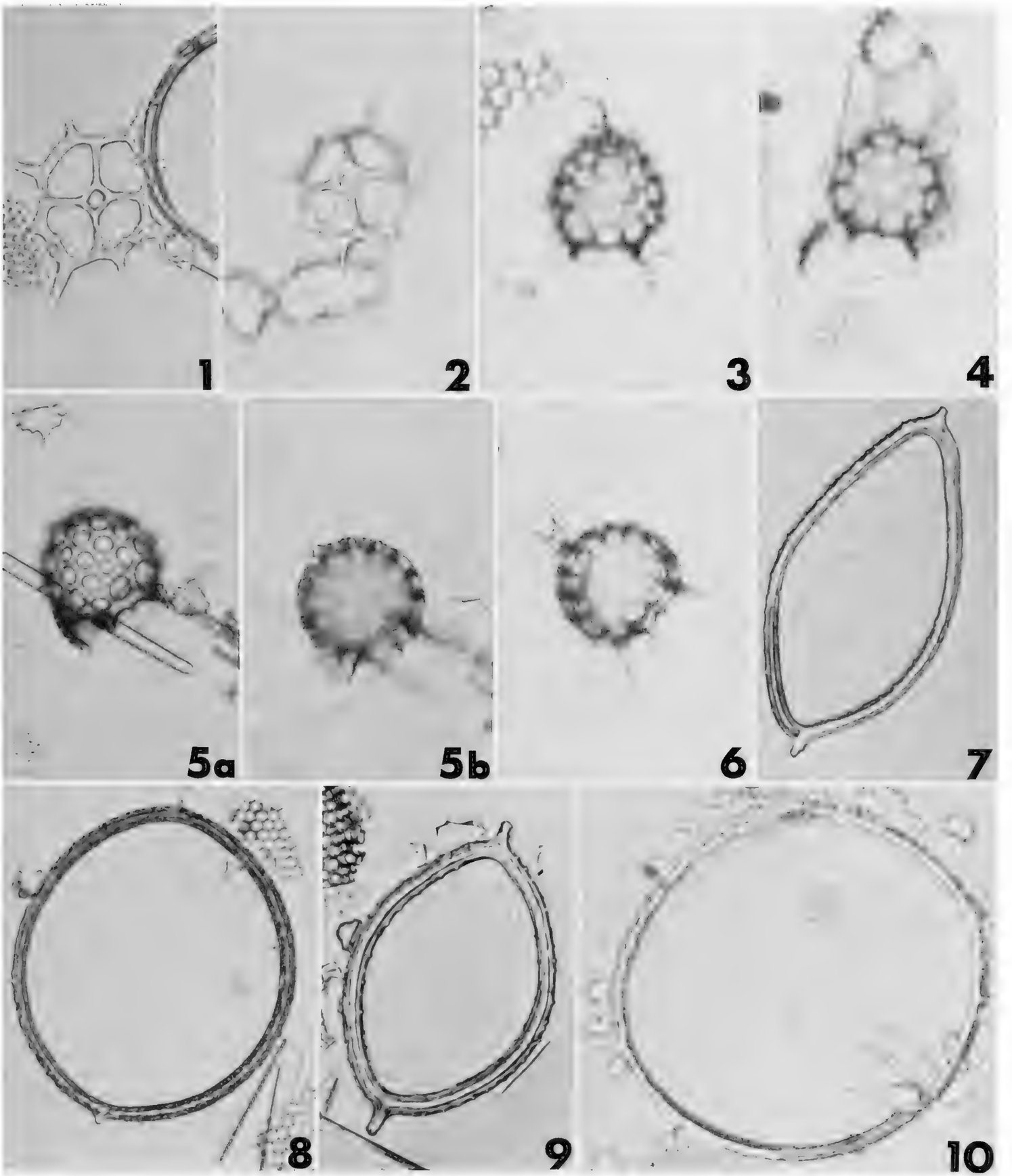
5
6a
6b
7
8
9a
9b

## PLATE 26

1, 2. *Distephanus stauracanthus* Ehrenberg, PA 31-198′2″
3, 4, 6. *Halicalyptra picassoi* (Stradner) Dumitrică: 3, 4, RA 13-163′8″; 6, RA 13-164′8″
5. *Halicalyptra picassoi* (Stradner) Dumitrică: *a*, high focus; *b*, mid-focus; RA 13-163′8″
7–10. *Mesocena* cf. *M. elliptica* (Ehrenberg) Ehrenberg: 7, RA 13-179′; 8, PA 31-205′4″; 9, RA 13-176′; 10, PA 31-198′2″. Note the variability in size and shape.

(All photographs at the same magnification, scale = 0.05 mm)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10

# Key Foraminifera from Upper Oligocene to Lower Pleistocene Strata of the Central Atlantic Coastal Plain

*Thomas G. Gibson*

ABSTRACT

Biostratigraphically important planktonic and benthic foraminiferal species from strata of late Oligocene to early Pleistocene age in the central Atlantic Coastal Plain are described and illustrated. Thirty planktonic species are used, in conjunction with a few radiometric ages, to date the strata. The ages derived are: "Silverdale" beds of latest Oligocene age; Pungo River and Calvert formations of late early to early middle Miocene age; Choptank Formation of middle middle Miocene age; St. Marys Formation of late middle to early late Miocene age; "Virginia St. Marys" beds of late Miocene age; Yorktown Formation of early to late(?) Pliocene age; and uppermost "Yorktown," Croatan, and Waccamaw formations of late Pliocene and early Pleistocene age.

Thirty-seven species and subspecies of benthic Foraminifera important for regional correlation are described, and ranges are given for this area. New species described are *Bolivina pungoensis*, *Bolivinopsis fairhavenensis*, *Epistominella pungoensis*, *Cibicides cravenensis*, *C. croatanensis*, *C. pungoensis*, *Svratkina croatanensis*, *Nonion calvertensis*, *Florilus chesapeakensis*, and *Elphidium neocrespinae.* New subspecies described are *Nonion advenum pustulosum* and *Elphidium latispatium pontium.*

*Thomas G. Gibson (United States Geological Survey), National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560.*

## Introduction

The age assignments of Cenozoic strata in the Atlantic Coastal Plain have been determined primarily from molluscan data. Although numerous molluscan groups, including the pectens, *Astarte*, and *Crassatella*, are valuable in correlation within the Atlantic Coastal Plain, the lack of molluscan species common to North America and Europe limits correlation with the European stratotype sections for the Oligocene, Miocene, Pliocene, and Pleistocene. Many benthic foraminiferal species are common to both areas, but species ranges generally are too long for the refined correlation desired.

This study used planktonic Foraminifera to correlate Atlantic Coastal Plain strata with intercontinental planktonic foraminiferal zones and the European stratotypes of Cenozoic stages. Gibson (1967), Akers (1972), and Hazel (1977) assigned some of the strata to planktonic zones. Strata ranging in age from late Oligocene to early Pleistocene and extending from Maryland to southern North Carolina were examined. Unfortunately, planktonic specimens are rare in many of the outcropping sections because of the shallow-water environment of deposition. This scarcity, combined with the cool-water nature of most of the assemblages, makes correlation difficult. The examination of large samples, however, pro-

duced rare but biostratigraphically important specimens in many of the formations. Radiometric ages supplement the foraminiferal data in some of the formations.

Key benthic species are proposed for correlation within the region and should prove valuable for dating subsurface sections. Thirty-seven benthic species that characterize one or more formations are discussed, and the range of each within the study area is given. Some of the species have greater ranges in other geographic and environmental areas. Species from well samples near the Atlantic Coast allow cross-indexing of the characteristic shallow-water species found in outcrops, and should serve as faunal links to assemblages found in strata on the Atlantic Continental Shelf.

Type specimens and all specimens illustrated here are deposited in the USNM collections of the National Museum of Natural History, Smithsonian Institution.

Acknowledgments.—The drawings are by Larry Isham of the National Museum of Natural History and Jeffrey Lund and Elinor Stromberg of the U.S. Geological Survey. Susann Braden, Walter Brown, and Mary-Jacquelyn Mann of the National Museum of Natural History took the SEM photographs. Well samples were supplied by Philip Brown of the U.S. Geological Survey. The author benefited from stimulating discussions on foraminiferal taxonomy with Bruce Hayward of the New Zealand Geological Survey. The manuscript was reviewed by Laurel Bybell, Thomas Cronin, and Joseph Hazel of the U.S. Geological Survey, and their helpful suggestions are incorporated.

## Age of the Formations

### Correlation with European Stages

The age placements by various authors for formations in the middle and late Tertiary show relative stability in the assignments of the older units, such as the Calvert Formation, and considerable, relatively recent changes in the placement of younger units, such as the Yorktown and Wacamaw formations. The correlation charts of Mansfield (1943) and Cooke, Gardner, and Woodring (1943) reflected the thinking at that time of many workers regarding the Atlantic Coastal Plain. In retrospect, however, the general stage of development of the invertebrate and vertebrate faunas appears to have been the only basis upon which these early workers correlated Atlantic Coastal Plain units with the European stages. Planktonic Foraminifera and nannoplankton were not used then, and radiometric dating was unavailable. Moreover, stages such as the Sarmatian and Pontian, with which the Yorktown Formation has been correlated (Mansfield, 1943) are represented by deposits formed in brackish to nonmarine environments in the eastern Mediterranean region. The type areas for these stages thus contain molluscan assemblages different from those found in the shallow-marine western Atlantic environments represented in the Yorktown Formation. Even within similar shallow marine environments, there are very few molluscan species common to both the Atlantic Coastal Plain and western Europe (Mongin, 1959:329).

The changes in age assignments made during the past 20 years include changes in interpretation of the age of the supposed later Miocene and younger formations. Although the recent use of planktonic groups has had a great effect on biostratigraphic studies, doubt about age assignments began because of the disparity in ages indicated by vertebrates and invertebrates. DuBar (1958:142) assigned a late Pleistocene age to the Caloosahatchee Formation of Florida, a unit that had been traditionally placed in the late Pliocene. His age assignment was based upon the occurrence of *Equus*, the modern horse, a genus considered indicative of a Pleistocene age. This change in age assignment disturbed those who studied invertebrates, because the large number of extinct molluscan species in the Caloosahatchee (as much as 50 percent, DuBar, 1958:137) suggested an older age. The resistance to accepting so many extinct species in Pleistocene strata probably is related to the Lyellian concept that less than 10 percent of the mollusks in the

Pleistocene are extinct. This resistance also appears to be related to the then accepted date of about one million years for the base of the Pleistocene, with the resultant rapid extinction of half of the assemblage. After DuBar's age assignment, common opinion among those who worked with invertebrates was as follows: If the Caloosahatchee were indeed Pleistocene in age, then the moderate similarity of its molluscan faunas to those of the Yorktown Formation would mean that the somewhat older Yorktown also must be interpreted as younger. Because the Yorktown Formation at that time was considered the "standard" unit of late Miocene age on the Atlantic Coastal Plain, a more recent date would indicate a Pliocene age. Although a Pleistocene age for the Caloosahatchee largely was discounted, the general result of this controversy was a new awareness of the uncertainties of previously accepted age assignments of Atlantic Coastal Plain Cenozoic strata.

Another opinion on the younger age of the Yorktown Formation resulted from the author's conversations with Remington Kellogg in the early 1960s concerning the age of a new baleen whale skeleton ("*Balaena*") found in the Yorktown Formation of Rice's Pit at Hampton Roads, Virginia. The baleen whale from the Yorktown Formation was similar to living baleen whales, and, in light of known rates of whale evolution, Kellogg could not resolve this similarity in terms of a late Miocene age for the Yorktown specimen. A possible explanation was that these beds in the upper half of the Yorktown Formation were younger than late Miocene.

The age significance of vertebrate specimens reported upon by Frank C. Whitmore, Jr. during the early 1960s also supported a post-late Miocene age for the Yorktown Formation. Whitmore (1965:A71) reported the following:

> Two mammalian fossils recently given to the Survey for identification have raised questions concerning the correspondence of age classifications of the coastal plain sediments based on vertebrate and on invertebrate fossils, respectively. A single lower horse molar, collected from the Yorktown Formation (upper Miocene) at Cobham Wharf, Va., has been identified by F.C. Whitmore, Jr., of the U.S. Geological Survey and M.F. Skinner, of the Frick Laboratory, American Museum of Natural History, as *Hipparion* cf. *H. eurystyle* Cope, of Clarendonian or early Hemphillian (early or early middle Pliocene) age. The possibility that part of the Yorktown may be of Pliocene age is further supported by the finding in 1960, at Hampton, Va., of a baleen whale of a type that seems too advanced for the Miocene.
>
> Part of a horse skull, found in the Caloosahatchee Formation in its type area near Labelle, Fla., has been identified by Whitmore as *Equus*, probably a mid-Pleistocene species. This find is of particular interest because the rich invertebrate fauna of the Caloosahatchee is generally regarded as being of Pliocene age.

Thus, most vertebrate evidence suggested that at least part of the Yorktown Formation was Pliocene in age. The tooth collected at Cobham Wharf, Virginia, however, was a float specimen from the modern beach rather than one collected in place from the Yorktown strata. Hence, doubt remained about whether it came from the fossiliferous Yorktown or from overlying sand units that tentatively were considered to be Pleistocene in age.

As a result of these questions concerning the age of the Yorktown Formation, the author examined planktonic Foraminifera from the Yorktown, because this group was being used to correlate with the European stages. On the basis of the sparse assemblages from the lower part of the Yorktown Formation, Gibson (1967:638) indicated a middle late Miocene age for these deposits. This age determination was based largely upon the identification of *Globorotalia mayeri* in the assemblages. On the basis of subsequent work on the "*Turborotalia*" lineages, particularly by Blow (1969), these specimens would now be placed in "*Turborotalia*" *acostaensis*, a group not widely recognized at that time. Even though the late Miocene age was applied to the lowermost part of the Yorktown, the age of the middle and upper part of the Yorktown Formation was considered unsettled at that time.

Therefore, pending additional concrete evidence for a Pliocene age for at least part of the Yorktown, the strata were questionably assigned a late Miocene age. This state of affairs was reflected in comments such as those in Gibson (1971:10):

With the occurrence of relatively large changes in the faunas, both macro and micro, in the overlying Yorktown beds, it is entirely possible that units placed in the upper Yorktown will range considerably into the Pliocene in age, but this reassignment will be dependent upon finding adequate planktonic assemblages.

Hazel (1971a) placed the youngest part of the Yorktown Formation in North Carolina, the beds along the Chowan River, into the early Pliocene. This was done on the assumption that the Yorktown Formation in Virginia was of late Miocene age, and that these younger beds along the Chowan (Mansfield, 1943) were, therefore, of early Pliocene age. How these beds correlated with the European stages of the upper Miocene and Pliocene was not demonstrated, except indirectly through strata in Florida. Hazel (1971a:8) stated:

Thus, it may be that the upper Miocene-lower Pliocene boundary in the Atlantic and Gulf Coastal Plain eventually will be revised further downward to include in the Pliocene more of the deposits that have been traditionally assigned to the upper Miocene.

Akers (1972) correlated the planktonic faunas from some Gulf and Atlantic Coastal Plain formations with planktonic zonations and stages in Europe. Akers (1972:32) concluded from the examination of a few assemblages from the Yorktown Formation that it was of Pliocene age, correlating with Blow's (1969) zones N19 and N20, and that the Waccamaw Formation in North Carolina, containing *Globorotalia truncatulinoides*, belonged to zone N22 of early Pleistocene age. Subsequent work by Akers and Koeppel (1973) on calcareous nannofossils supported a zone N20 date for the Yorktown Formation in Virginia and North Carolina. These age assignments also are supported by the present study.

The Waccamaw and Croatan formations are herein considered coeval with the Caloosahatchee Formation, and are all considered late Pliocene and early Pleistocene in age. The new age assignments for these formations, along with that for the Yorktown, bring into agreement, at least at the epoch level, the ages of the strata and are based on both the invertebrates and the vertebrates.

## Planktonic Foraminiferal Zonation

Much of the current worldwide correlation with the European stratotypes is based upon the planktonic Foraminifera, although the use of calcareous nannoplankton, diatom, radiolarian, and dinoflagellate correlations is increasing rapidly. Zonations based upon planktonic Foraminifera have been established in several different regions, for example by Bolli (1957) for Trinidad, Blow (1959) for Venezuela, and Jenkins (1960) for New Zealand. A summary of the land-based distributions and some early Deep Sea Drilling Program samples were presented by Blow (1969), who then established a zonation that was based upon all available data. Blow named the zones, using diagnostic or important species of planktonic Foraminifera, and also placed them in a numbered series, using N numbers for the later Cenozoic or Neogene zones and P numbers for the older Cenozoic or Paleogene zones. Although Jenkins and Orr (1972:1063) criticized the use of numbered zones as "unacceptable to existing stratigraphic codes," the use of the N and P zones as a form of shorthand has become widespread, although far from universal. Studies in nontropical waters, such as those of Poore and Berggren (1975) in the high latitudes of the northern Atlantic and Kennett (1973) in the cool-subtropical southwest Pacific, and even some workers in tropical areas, such as Jenkins and Orr (1972), had difficulty in recognizing some or many of Blow's zones and developed their own zonal sequence. Some attempt, however, was usually made to correlate the zones with Blow's (1969) sequence.

The ranges of the stratigraphically important planktonic species generally are similar in the various oceanic and continental areas, but some relatively minor differences and a few major differences in the initial appearance or the extinction of species are found. The range discrepancies important to this study are noted under the species, where applicable.

Studies of the planktonic Foraminifera found in the stratotype sections of the later Cenozoic in Europe and in the JOIDES cores have refined the

species ranges during the past 10 years. Some European stages containing good marine faunas including planktonic Foraminifera have been used as alternatives to more commonly used stages containing faunas of restricted environments. This is particularly true of the Sarmatian and Pontian stages, which were deposited in marginal marine to brackish water environments. Most authors now attempt correlations with other stages containing adequate marine invertebrate assemblages.

A better understanding of the ranges of planktonic Foraminifera has led to some changes in the stages to which zones are assigned. As a general rule, the zones have been shifted upward, either within the same stage or into a younger stage. An example of such a change, is the correlation of the Pungo River Formation of North Carolina. Gibson (1967) assigned these strata to the *Globigerinatella insueta* zone, then placed by Blow (1959:74) and Saito (1963, table 16) in the upper part of the Aquitanian. The present study supports the correlation of the Pungo River Formation with the *G. insueta* zone, but Berggren and Van Couvering (1974) placed this zone in the upper Burdigalian and lower Langhian stages. This study of the relationship of the planktonic zones to the stages in the later Cenozoic by Berggren and Van Couvering (1974), also integrated the radiometric dates with the sequence of planktonic foraminiferal zones, as shown in their figure 1.

The use of planktonic Foraminifera for correlation in the Miocene through Pleistocene strata of the Atlantic Coastal Plain is difficult, not only because planktonic specimens are extremely scarce (usually less than 1 percent), but also because most taxa that are present are cool-water species. Consequently it is difficult to recognize planktonic foraminiferal zones that are based on warm-water species. Most of the easternmost localities of the Coastal Plain are subsurface material or artificial exposures like those found in the Pungo River Formation in the Lee Creek Mine. In some of these easternmost localities, planktonic specimens are more common, composing 10 percent or more of the foraminiferal assemblage, reflecting deeper water environments. The clockwise circulation pattern of the North Atlantic does bring some warmer water faunal elements into the area, however, and a few specimens of important index species are found. Akers (1972) found two specimens of *Globorotalia truncatulinoides* in a large sample from Walkers Bluff in the Waccamaw Formation after 100 hours of examination. Most samples in this study present similar problems because the critical species may be represented by only one or several specimens at a locality. Although these low abundances are not desirable for biostratigraphic work, the use of rare specimens for zonation is the best means of interregional correlation at the present time. The scarcity of specimens and low reliability of correlation should be kept in mind when working with the placement of some of the strata in this area. An abundance of planktonic specimens at several localities yielded relatively large numbers of individuals belonging to critical species and thus provides fairly precise and reliable dates.

Important localities mentioned in the text are shown in Figure 1. The interpretations of the ages of the strata are given in Gibson's figure 2 (p. 38 herein). A summary of the assemblages from each formation and the resulting age assignments are as follows.

### Pungo River Formation

The only known outcrop of this formation is an artificial one in the Lee Creek Mine of Texasgulf Inc. near Aurora, North Carolina (Figure 1, loc. 15). Additional faunas from the Pungo River Formation have been obtained from the Gatesville Well in northeastern North Carolina and the Moores Bridge well near Norfolk in southeastern Virginia (Figure 1, loc. 11).

In the Lee Creek Mine the Foraminifera are highly phosphatized in the phosphatic sands that are prevalent in the lower and middle part of the formation. Foraminifera and some mollusks, primarily calcitic pelecypods, are found in limy intervals in the upper 12 feet (3.7 m) of the formation.

Important planktonic foraminiferal species from the Pungo River strata in the Lee Creek Mine include the following: *Cassigerinella chipolensis* (Cushman and Ponton), *Globigerina euapertura* Jenkins, *G. woodi woodi* Jenkins, *Globigerina* species cf. *G. angulifficinalis* Blow, *Globigerinoides altiaperturus* Bolli, *Globorotalia peripheroronda* Blow and Banner, *G. scitula praescitula* Blow, and "*Turborotalia*" *birnageae* (Blow).

The probable age for this assemblage is from the latter part of zone N7 to the latter part of zone N8 of Blow (1969) (Gibson's figure 2 on p. 38 herein). An age younger than N8 is not likely because of the presence of *Globigerina euapertura* and *Globigerinoides altiaperturus*, neither of which is known from strata younger than N8, and by the absence of *Orbulina* which is commonly regarded as marking the beginning of N9. The upper part of the Pungo River Formation in the Lee Creek Mine is thus considered to belong to planktonic zone N8, or latest early Miocene in age. The age of the underlying phosphatic sand units in the mine is unknown because of the poor preservation of the Foraminifera; the amount of time for and rapidity of deposition of the phosphatic sands and diatomaceous units is an intriguing, but presently unanswerable, question.

The northern limit of the Pungo River Formation occurs in the Norfolk, Virginia, Moores Bridge well area (Figure 1, loc. 11) drilled by the U.S. Geological Survey. The strata yielded a foraminiferal assemblage similar to that found at the Lee Creek Mine. In addition, rare specimens of *Globigerinatella insueta* were found at a depth of 581 feet (177 m). The age of these strata also is considered to be zone N8. At this locality, the Pungo River Formation rests directly upon Paleogene rocks, indicating that the oldest age of the formation in this area is late early Miocene (N8).

To the northeast of the Lee Creek Mine, Abbott and Ernissee (this volume) found strata containing diatoms; the lower part of the strata correlates with zone N8 or N9 and the upper part with zone N11, indicating deposition of the younger strata of the Pungo River Formation close to the area of the Lee Creek Mine. As the top of the Pungo River section in the Lee Creek Mine has an erosional surface (Gibson, 1967:636), it is possible that the younger part of the formation also was deposited there and later eroded.

In summary, the distribution of strata assigned to the Pungo River Formation containing zone N8 planktonic Foraminifera is widespread, extending from south of the Neuse River in North Carolina northward to the area near Norfolk, Virginia. Strata with zone N11 planktonic assemblages are found in the central part of the Albemarle embayment in North Carolina. Strata of this age, however, may have been more extensive in the past, having been eroded in areas similar to the Lee Creek Mine and remaining unrecognized in other areas. Strata belonging to the intervening zones N9 and N10 have not been found.

## Calvert Formation

The only diagnostic planktonic foraminiferal assemblages in the Calvert Formation come from beds 10 to 12 of Shattuck (1904) in the Calvert Cliffs along Chesapeake Bay in Maryland. The most abundant faunas come from bed 10, whereas beds 1 to 9, and the uppermost beds, 13 to 15, yielded few specimens. The following important species are found in bed 10 in the Calvert Cliffs: *Globigerina praebulloides pseudociperoensis* Blow, *Globigerinoides altiaperturus* Bolli, *G. sicanus* de Stefani, and *Praeorbulina glomerosa glomerosa* (Blow).

These species indicate an age of upper zone N8

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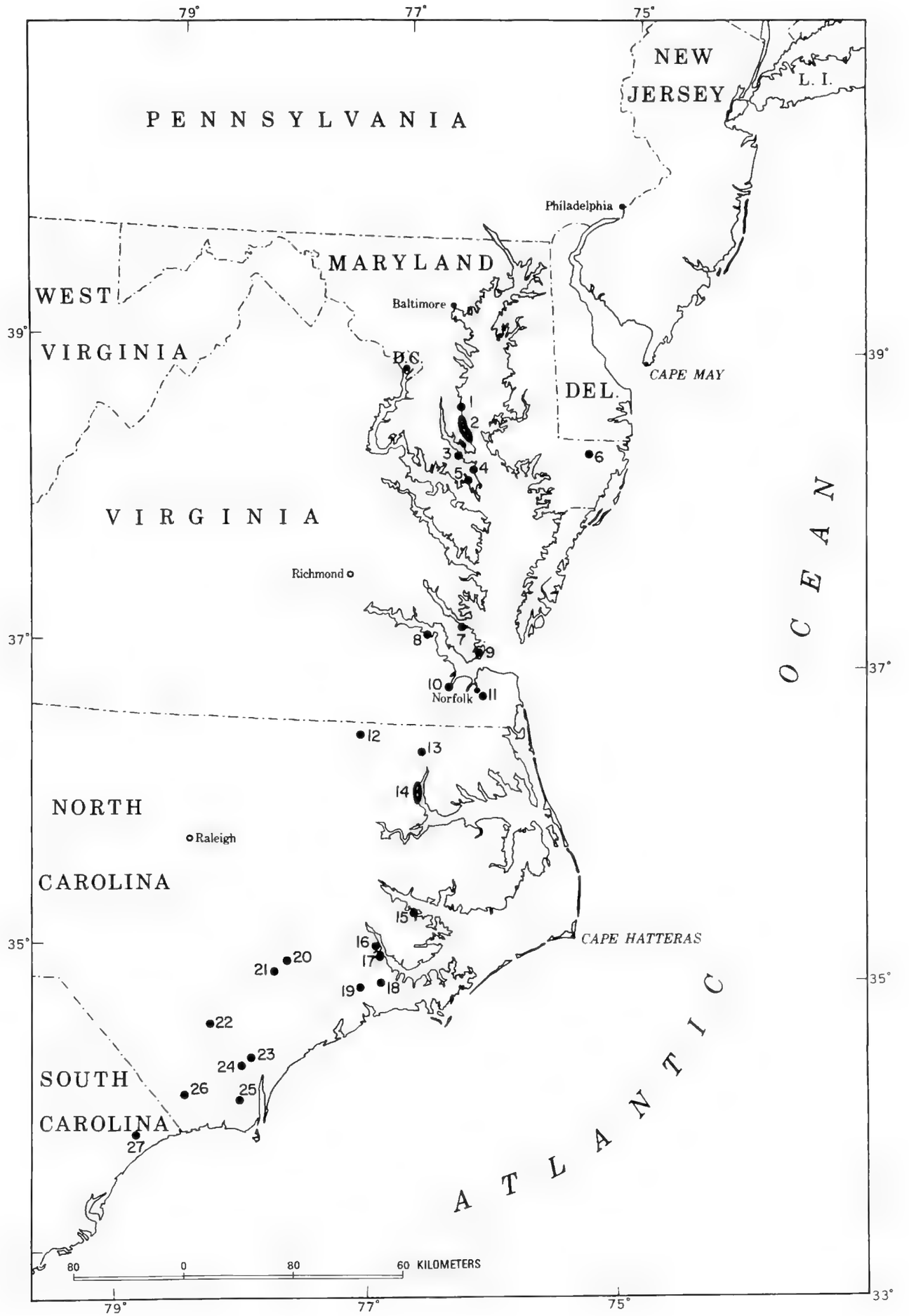
Figure 1—Location of collecting localities mentioned in text (Maryland: 1 = Randle Cliffs, 2 = Calvert Cliffs, 3 = Jones Wharf, 4 = Langleys Bluff, 5 = St. Marys River, 6 = Hammond Well. Virginia: 7 = Yorktown, 8 = Cobham Wharf, 9 = Rice's Pit, 10 = Suffolk, 11 = Moores Bridge Well, Norfolk. North Carolina: 12 = Murfreesboro, 13 = Gatesville Well, 14 = Chowan River outcrops, 15 = Lee Creek Mine, 16 = New Bern, 17 = James City, 18 = Croatan National Forest, 19 = Long Point, 20 = Barwick Farm, 21 = Natural Well, 22 = Walkers Bluff, 23 = Neils Eddy Landing, 24 = Acme, 25 = Pierce Brothers Quarry, 26 = Old Dock. South Carolina: 27 = Tillys Lake).


79°
77°
75°
NEW JERSEY
L. I.
PENNSYLVANIA
Philadelphia
MARYLAND
WEST VIRGINIA
Baltimore
39°
VIRGINIA
D.C.
DEL.
CAPE MAY
1
2
3
4
5
6
VIRGINIA
Richmond
37°
7
8
9
10
Norfolk
11
12
13
14
NORTH CAROLINA
Raleigh
15
16
17
CAPE HATTERAS
35°
18
19
20
21
22
23
24
25
26
SOUTH CAROLINA
27
ATLANTIC OCEAN
80 0 80 60 KILOMETERS
33°

to lower zone N9 for bed 10. The absence of *Orbulina* probably means an age of upper zone N8. As a large part of the *Orbulina* lineage is represented in the Calvert Cliffs, the absence of *Orbulina*, because of environmental causes, probably can be discounted. In beds 11 and 12 of the Calvert Formation, specimens belonging to *Praeorbulina glomerosa circularis* and *Orbulina suturalis* appear, indicating a probable lower zone N9 placement for these strata. Beds 13 to 15 at the top of the Calvert Formation and beds 1 to 9 at the base do not contain diagnostic planktonic species, but the general similarity in the stage of evolution of molluscan species suggests closeness in age to the adjacent dated beds.

In summary, the probable age for bed 10 of the Calvert Formation is zone N8, and that for the overlying beds 11 and 12 is probably of lower zone N9. The amount of time represented in the beds below bed 10, which includes a sequence of diatomaceous units 60 feet (18 m) thick, or more, is unknown at the present time.

### Choptank Formation

Planktonic specimens are extremely rare in the Choptank Formation. The only specimens found to date belong to long-ranging species of *Globigerina*, and correlation with Blow's planktonic zonal sequence is not possible.

A tentative lower age limit for the formation was established on the following basis. The youngest age established for the Calvert Formation in Maryland is lower zone N9 for bed 12. There is disagreement as to whether a significant unconformity exists between the Calvert and Choptank formations (Gernant, 1970:7). The abrupt appearance in the basal Choptank Formation of several species of benthic Foraminifera that are absent in the uppermost part of the Calvert may indicate a time break (Gibson, 1962:13, 63). R.M. Forester (U.S. Geological Survey, pers. comm., 1976) also noticed that some lineages of ostracodes change significantly across the Calvert-Choptank boundary, indicating a possible hiatus. For the present, the contact is considered unconformable, and the basal beds of the Choptank are tentatively dated as belonging in zone N12.

Direct paleontological evidence is also inadequate to determine the age of the upper beds of the Choptank Formation. A K/Ar age determination of 12.0 ± 0.5 my from the overlying St. Marys Formation in Maryland was reported by Blackwelder and Ward (1976:5). This late middle Miocene date for the overlying St. Marys, if substantiated by further work, and the early middle Miocene date for the top of the underlying Calvert places the Choptank in approximately the middle part of the middle Miocene (Gibson's figure 2 on p. 38 herein).

### St. Marys Formation

No diagnostic planktonic foraminiferal species have been recognized among the rare specimens found in the St. Marys Formation. A K/Ar date of 12.0 ± 0.5 my (Blackwelder and Ward, 1976:5) for beds along the St. Marys River in Maryland is the only evidence on the age of this unit. The radiometric date places these beds in the upper part of the middle Miocene. The stratigraphically higher parts of the formation along the St. Marys River show sufficient change in the molluscan fauna to suggest the possibility of a younger, early late Miocene age (Gibson, in prep.).

### "Virginia St. Marys" Beds

Diagnostic planktonic foraminiferal species have not been found in the "Virginia St. Marys" beds of Mansfield (1943) (see Gibson, 1971). The late middle to possible early late Miocene age for the underlying St. Marys Formation in Maryland and the early Pliocene date (planktonic zone N19) for overlying zone 1 beds of the Yorktown of Mansfield (1943) bracket these strata and indicate a late Miocene age. A K/Ar date of 8.7 ± 0.4 my for the middle part of the "Virginia St. Marys" sequence, reported by Blackwelder and Ward (1976:5), supports this late Miocene age assignment. Changes in the molluscan faunas

through these strata, particularly the pectens (Gibson, in prep.), indicate that a significant amount of late Miocene time may be represented.

Strata of the "Virginia St. Marys" sampled in northern North Carolina in a well near Gatesville in Gates County (Figure 1, loc. 13) contained moderately abundant planktonic specimens. Important species in the assemblage include *Globorotalia merotumida* Blow and Banner and *"Turborotalia" acostaensis acostaensis* Blow. Specimens approaching and within the range of variation of *Globorotalia plesiotumida* Blow and Banner occur, but specimens of *G. merotumida* dominate. These species indicate a probable placement in zone N17 for the upper beds of the "Virginia St. Marys" in North Carolina.

### Yorktown Formation

The *Placopecten clintonius* zone or zone 1 of the Yorktown Formation of Mansfield (1943) contains a moderately abundant planktonic assemblage that includes some stratigraphically important species: *Globigerina apertura* Cushman, *Globoquadrina altispira altispira* (Cushman and Jarvis), *Globorotalia puncticulata* (Deshayes), *Globorotalia* species cf. *G. crassula* Cushman and Stewart, *Sphaerodinellopsis seminulina seminulina* (Schwager), *S. subdehiscens subdehiscens* (Blow), and *"Turborotalia" acostaensis humerosa* (Takayanagi and Saito).

The presence of *Globorotalia puncticulata* in these assemblages suggests a placement of zone N19 or later (see p. 373). The upper range of *Sphaerodinellopsis seminulina seminulina* in the Atlantic is considered to be the upper part of zone N20 (Poag, 1972b:492, 493, 499; Berggren and Amdurer, 1973:353, figs. 4, 7, 8). Blow (1969:338) reported an upper range of zone N20 in land-based sequences, but into lower zone N21 in deep-sea sequences. If these data are correct, this subspecies is indicative of zone N20, or older, age for the *Placopecten clintonius* zone of Mansfield (1943). Additional support comes from the occurrence of *Globigerina apertura*, which has a reported upper range of zone N20. *Globoquadrina altispira altispira* was considered by Blow (1969:339) to range into the lower part of zone N21 in oceanic deposits, but was probably not younger than lower zone N20 in land-based sequences. An upper range of lower zone N21 is commonly found for *Sphaerodinellopsis subdehiscens subdehiscens* also. The presence of *"Turborotalia" acostaensis* in the assemblage also indicates an early Pliocene age. Parker (1967:165) reported that species as ranging to the end of zone N18, but Jenkins and Orr (1972:1066, 1096) extended its range into zones N19/20, and Poag (1972b:485, 511) into zone N21. This assemblage appears to be indicative of an early Pliocene zone N19/20 age, and this is the age assigned to the *Placopecten clintonius* zone. A radiometric date of 4.4 ± 0.2 my was obtained from Yorktown strata immediately overlying this zone (Blackwelder and Ward, 1978:8), and this age closely corresponds to the planktonic foraminiferal assignment.

The overlying Yorktown strata of the *Turritella alticostata* zone or zone 2 of Mansfield (1943) and the Duplin Formation, the equivalent of the upper part of the Yorktown in southern North Carolina and southward, are younger. The correlation of these strata with Blow's zonation is difficult at present because of the scarcity of biostratigraphically diagnostic planktonic species. Most of the planktonic specimens in these strata belong to the long-ranging species *Globigerina bulloides*, *Globigerinoides trilobus*, and *G. ruber*. Among the few species that have shorter ranges is *Globigerina apertura*, which has a reported upper range through zone N20. The type area for this species is near Suffolk, Virginia, in the Yorktown deposits that Mansfield (1943) placed high in his zone 2. Subsequent work has supported this placement. *Globorotalia puncticulata*, which has an upper range of zone N21, also occurs in strata of Mansfield's zone 2. Specimens of *G. puncticulata* from zone 2 show characteristics transitional to those of *"Turborotalia" inflata*, but specimens of the latter species are absent from zone 2. *"Turborotalia" inflata* is indicative of zone 21 and younger ages. The occurrence of *G. puncticulata* and the absence of *"Turborotalia" inflata*, although meager evidence, could indicate a late zone N19/20 to early

zone N21 age for the upper part of Mansfield's zone 2 of the Yorktown. Only the occurrence of *Globorotalia hirsuta hirsuta* in strata of zone 2 at the type area of the Yorktown Formation in the bluffs at Yorktown, Virginia, conflicts with this zonal assignment. This subspecies is usually considered characteristic of zone N22 and younger strata, but here occurs in strata tentatively assigned to late zone N20 to early zone N21. The specimens appear to fall well within the range of variation of this subspecies (Plate 3: figures 5–7).

### Uppermost "Yorktown," Croatan, and Waccamaw Formations

The uppermost part of the "Yorktown" Formation, which is exposed along the Chowan River in northeastern North Carolina, the Croatan Formation at the Lee Creek Mine and southeast of New Bern, North Carolina, and the Waccamaw Formation in southern North Carolina and northern South Carolina appear to be of approximately equivalent age (Gibson's Figure 2, p. 38 herein). This correlation is based upon the stratigraphic distribution of pectens (Gibson, in prep.) and benthic Foraminifera (Figure 2). Planktonic Foraminifera are rare in these formations because of the very shallow water environment of deposition. Akers (1972:36, 38) reported rare specimens of "*Turborotalia*" *inflata* and *Globorotalia truncatulinoides* from the Waccamaw Formation at Walkers Bluff. The first appearance of *G. truncatulinoides* commonly is used to mark the base of the Pleistocene, although there is some controversy about how close to the boundary it occurs. In the upper part of the Croatan Formation at the Lee Creek Mine, a single specimen strongly resembling *G. truncatulinoides* was found. At least these parts of the formations apparently belong to the lower Pleistocene or zone N22.

Evidence that these deposits are no younger than zone N22 is the occurrence of *Globigerinoides obliquus* (Akers, 1972:34). Benthic foraminiferal species characteristic of zone 2 of the Yorktown Formation are found in the lower part of the Croatan Formation in the Lee Creek Mine, but they are not found in the upper part of the section. These faunal changes suggest that the lower part of the Croatan is somewhat older than the zone N22 assignment for the upper part. Because no specimens of *G. truncatulinoides* have been found in the lower beds, and in consideration of the changes in the benthic assemblages, the lower beds are placed in the upper Pliocene zone N21. Thus, the Croatan Formation and equivalent units appear to range in age from late Pliocene into early Pleistocene. The upper Pliocene strata may correlate with the Bear Bluff Formation of DuBar et al. (1974) as suggested by Hazel (1977:375). The younger strata, tentatively assigned to zone N22 of early Pleistocene age, on the basis of planktonic foraminiferal evidence, presently are recognized only in the upper part of the Croatan Formation in the Lee Creek Mine and in the Waccamaw Formation in southern North Carolina. Evidence from the pectens (Gibson, in prep.) indicates that the uppermost "Yorktown" beds at Mt. Gould along the Chowan River also may be included in this zone.

## Key Benthic Species

Although benthic foraminiferal species generally have greater ranges and are more closely controlled environmentally than their planktonic counterparts, some benthic species were recognized by Gibson (1962) to be widespread throughout only one or several of the formations in this area. These species are useful guides, particularly in the subsurface where molluscan data are largely unavailable. Examination of several hundred samples in the Atlantic Coastal Plain from Maryland to North Carolina, both from outcrops and the subsurface, indicates that a number of benthic species are each characteristic of the upper Oligocene, Miocene, Pliocene, and lower Pleistocene formations in this area. Some diagnostic species are known only from the unit(s) in this area; others are found in coeval deposits in other areas in the Western Hemisphere or elsewhere; and still others have a restricted range here but broader ranges in other areas. The par-

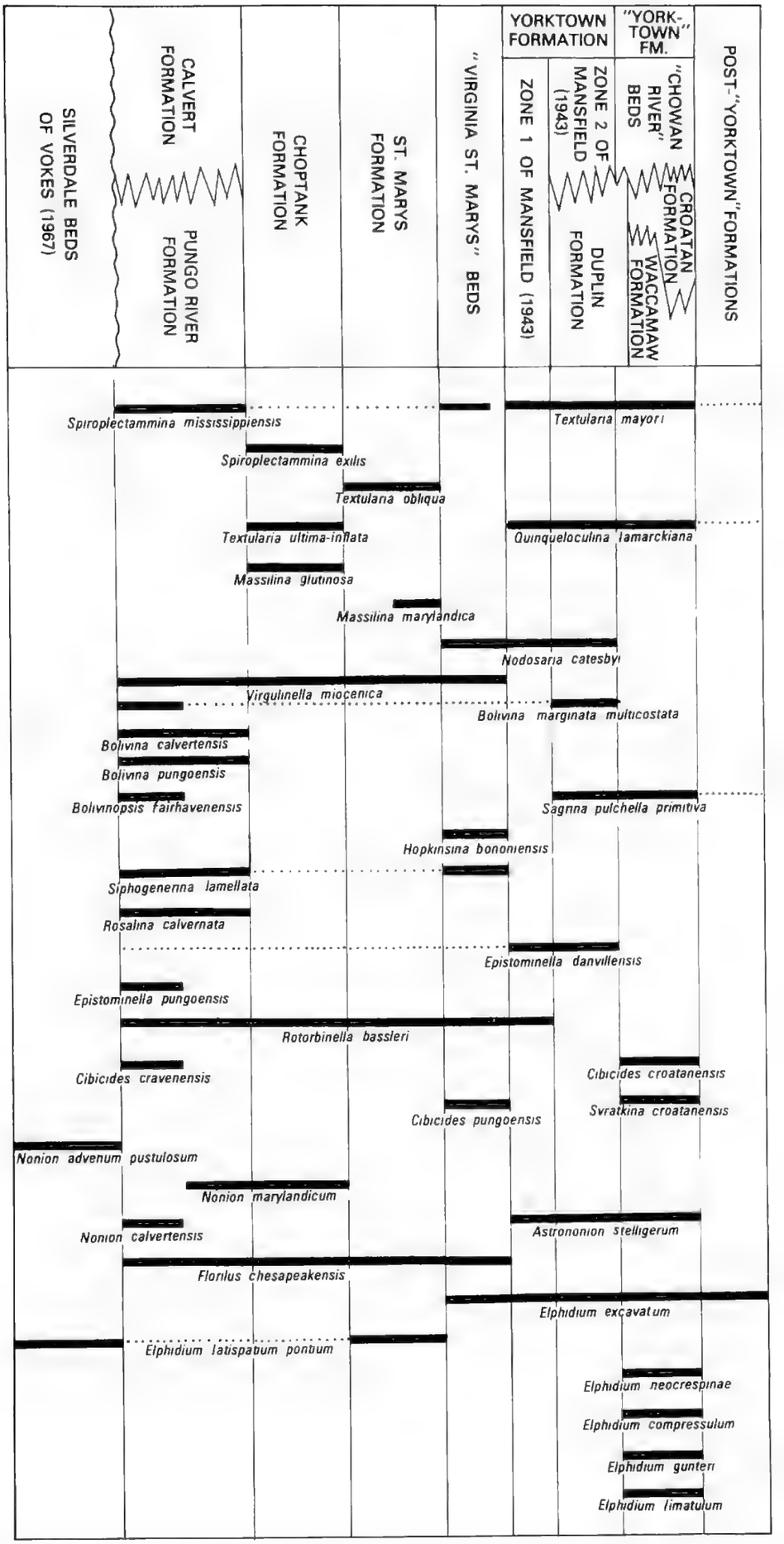



FIGURE 2.—Distribution of key benthic foraminiferal species in upper Oligocene through lower Pleistocene strata in the central Atlantic Coastal Plain.

ticular situation for each species is noted in the systematic section. Hazel (1977) noted the significant ostracodes for the Pliocene and early Pleistocene in this area.

Some species are present in both surface and subsurface samples, but others are found mostly only in one or the other. This results from the general eastward dip of the strata and increasing depth of deposition in the strata to the east. Thus the shallower water environments are generally found farther west in the outcrop belt. The general climatic pattern in the area was one of mild temperate conditions and some warmer fluctuations through the Miocene and earliest Pliocene. A general warming trend began in the early Pliocene and extended through late Pliocene and earliest Pleistocene time, when warm temperate to subtropical conditions were reached in southern North Carolina (Gibson, 1967:647; Hazel, 1971b:373). The warming trend allowed some species to make their first appearance at a later time in this area than in warmer areas to the south. Thus, some key species in this area have greater ranges in Florida and in other warm regions.

Many of the key species are relatively common in the assemblages, greater than 5 percent, but some are rare, making up less than 1 percent of the assemblage, as noted in the systematic section.

Some key species diagnostic of the deeper water environments of the formations in the subsurface of the Coastal Plain may aid in correlation with strata on the Continental Shelf, and serve as a bridge between the shallower water outcrop and deeper water offshore sections.

Species diagnostic of each formation or part thereof are shown in Figure 2. A general distribution is given (pp. 360–364), and detailed distributions are discussed in the systematics section.

### Silverdale Beds of Vokes, (1967)

These onshore strata represent very shallow marine environments, where a few species dominate the assemblages. Fortunately, the dominant species are diagnostic for this unit. They include the two new subspecies, *Nonion advenum pustulosum*, restricted to this unit, and *Elphidium latispatium pontium*, which occurs in this unit and again in the younger St. Marys Formation, and *Discorbitura dignata*, which is not found above this unit.

### Calvert and Pungo River Formations

Because of the large geographic area covered by the two formations and the variety of environments represented, distributional patterns of the key species are variable. *Bolivina calvertensis, Bolivinopsis fairhavenensis,* new species, and *Epistominella pungoensis*, new species, are restricted to these two formations. *Spiroplectammina mississippiensis* occurs only in these two formations in this area, but is found in other regions. *Rosalina cavernata* and *Nonion calvertensis*, new species, are found only in the Calvert Formation. *Bolivina pungoensis*, new species, and *Cibicides cravenensis*, new species, are found only in the lower part of the Pungo River Formation. *Virgulinella miocenica, Rotorbinella bassleri,* and *Florilus chesapeakensis,* new species, range upwards from these formations, but serve to differentiate them from the underlying Oligocene units and, in those places where the Choptank and St. Marys formations are absent, from various parts of the overlying Yorktown Formation.

### Choptank Formation

Because of the presently relatively restricted geographic distribution of this formation (Gibson, 1971) and generally similar shallow-water environments, the key species are found in most samples. They include *Spiroplectammina exilis, Textularia ultima-inflata, Massilina glutinosa,* and *Nonion marylandicum*, although the latter is also found rarely in the upper part of the Calvert.

### St. Marys Formation

Most assemblages from the St. Marys Formation are composed of species that are found also in the underlying formations and in the lower part of the overlying Yorktown Formation, mak-

ing it difficult to recognize this formation in the subsurface. However, the presence of *Textularia obliqua*, *Massilina marylandica*, and *Elphidium latispatium pontium*, new subspecies, and the absence of the common key species in the Choptank serve to identify the unit in most samples.

### "Virginia St. Marys" Beds

One important subspecies that first appears in the "Virginia St. Marys" strata and still lives today is *Elphidium excavatum clavatum.* This subspecies appears abruptly and is so abundant (forming 20 to 40 percent of the assemblages) that it is a valuable guide for separating these strata from earlier ones. The co-occurrence of this species with *Virgulinella miocenica* marks the "Virginia St. Marys." *Hopkinsina bononiensis* and *Cibicides pungoensis*, new species, are only found in the "Virginia St. Marys" in the subsurface of northeastern North Carolina.

### Yorktown Formation and Equivalents

This formation spans both considerable time and various environments, resulting in significant geographic changes in the benthic assemblages. Although some species are restricted stratigraphically to various parts of the formation, most appear in the underlying formations and are living today. Zone 1 of Mansfield (1943) is characterized by the first appearance of *Textularia mayori, Quinqueloculina lamarckiana, Nodosaria catesbyi, Epistominella danvillensis,* and *Astrononion stelligerium*, along with the co-occurrence of *Rotorbinella bassleri.* Zone 2 of Mansfield (1943) is marked by the restricted occurrence in this area of *Bolivina marginata multicostata*, the last appearance of *Nodosaria catesbyi* and *Epistominella danvillensis*, and the first occurrence of *Sagrina pulchella primitiva.* The youngest beds of the "Yorktown" along the Chowan River, as well as the coeval Croatan and Waccamaw formations to the south, contain a number of species restricted to those strata, including three new species, *Cibicides croatanensis, Svratkina croatanensis,* and *Elphidium neocrespinae,* and *Elphidium compressulum* and *E. limatulum*, all of which are found in these strata and in the Duplin Formation. *Elphidium gunteri* is restricted to these units, although it has a greater range in warmer environments.

## Systematic Descriptions

Generic concepts as applied to planktonic Foraminifera are unsettled at this time. Some of the common generic names, such as *Globorotalia*, have been applied to several groups of species that occur at significantly different times in the fossil record and have no known connecting species; this leads one to doubt strongly any phylogenetic linkage between the groups. Other genera, such as *Turborotalia*, are used as morphologic types (usually on the basis of one or possibly several distinctive features) that occur at different times in a number of apparently separate lineages, which means that they are definitely polyphyletic. Even the commonest name, *Globigerina*, was considered by Fleisher (1974:1009, 1018) to include a number of polyphyletic units, which he discriminated largely on the basis of wall texture. Pending further study and revision, most of the generic names currently used can be considered convenient holding names for an uncertain number of species. Illuminating discussions on the generic problems are found in Fleisher (1974), Parker (1967), and Stainforth et al. (1975).

Placement of species of benthic Foraminifera here follows a classification of genera and families modified from Loeblich and Tappan (1964). The rigid application by Loeblich and Tappan of wall structure as the dominant character in higher level foraminiferal systematics has led to the placement of apparently closely related species in different genera and families. Towe and Cifelli (1967) showed the difficulties in applying optical studies of wall structure, such as those of Loeblich and Tappan, to electron microscope studies of the wall. Buzas (1965, 1966) found both granular and radial wall structure in species of *Elphidium*, as did Hansen (1972a) in *Turrilina* and Feyling-Hansen and Buzas (1976) in *Cassidulina.* Information

from studies such as these indicates that groupings and separations based solely upon wall structure should be revised.

Order FORAMINIFERIDA Eichwald, 1830
  Superfamily GLOBIGERINACEA Carpenter, Parker, and Jones, 1862
    Family GLOBIGERINIDAE Carpenter, 1862
      Genus *Cassigerinella* Pokorný, 1955
      Genus *Globigerina* d'Orbigny, 1826
      Genus *Globigerinatella* Cushman and Stainforth, 1945
      Genus *Globigerinita* Bronnimann, 1951
      Genus *Globigerinoides* Cushman, 1927
      Genus *Globoquadrina* Finlay, 1947
      Genus *Globorotalia* Cushman, 1927
      Genus *Orbulina* d'Orbigny, 1839
      Genus *Praeorbulina* Olsson, 1964
      Genus *Pulleniatina* Cushman, 1927
      Genus *Sphaeroidinellopsis* Banner and Blow, 1959
    Family GLOBOROTALIIDAE Cushman, 1927
      Genus *Turborotalia* Cushman and Bermudez, 1949
  Superfamily LITUOLACEA de Blainville, 1825
    Family TEXTULARIIDAE Ehrenberg, 1838
      Genus *Spiroplectammina* Cushman, 1927
      Genus *Textularia* Defrance, 1824
      Genus *Bolivinopsis* Yakovlev, 1891
  Superfamily MILIOLACEA Ehrenberg, 1839
    Family MILIOLIDAE Ehrenberg, 1839
      Genus *Quinqueloculina* d'Orbigny, 1826
      Genus *Massilina* Schlumberger, 1893
  Superfamily NODOSARIACEA Ehrenberg, 1838
    Family NODOSARIIDAE Ehrenberg, 1838
      Genus *Nodosaria* Lamarck, 1812
  Superfamily BULIMINACEA Jones, 1875
    Family BOLIVINITIDAE Cushman, 1927
      Genus *Bolivina* d'Orbigny, 1839
    Family UVIGERINIDAE Haeckel, 1894
      Genus *Hopkinsina* Howe and Wallace, 1932
      Genus *Sagrina* d'Orbigny, 1839
      Genus *Siphogenerina* Schlumberger, 1882
  Superfamily DISCORBACEA Ehrenberg, 1838
    Family DISCORBIDAE Ehrenberg, 1838
      Genus *Rotorbinella* Bandy, 1944
      Genus *Epistominella* Husezima and Maruhasi, 1944
      Genus *Rosalina* d'Orbigny, 1826
      Genus *Cancris* Montfort, 1808
  Superfamily ROTALIACEA Ehrenberg, 1839
    Family ELPHIDIIDAE Galloway, 1933
      Genus *Elphidium* Montfort, 1808
  Superfamily ORBITOIDACEA Schwager, 1876
    Family CIBICIDIDAE Cushman, 1927
      Genus *Cibicides* Montfort, 1808
  Superfamily CASSIDULINACEA d'Orbigny, 1839
    Family CAUCASINIDAE Bykova, 1959
      Genus *Virgulinella* Cushman, 1932
    Family NONIONIDAE Schultze, 1854
      Genus *Astrononion* Cushman and Edwards, 1937
      Genus *Florilus* Montfort, 1808
      Genus *Nonion* Montfort, 1808
    Family ALABAMINIDAE Hofker, 1951
      Genus *Svratkina* Pokorný, 1956

## Genus *Cassigerinella* Pokorný, 1955

### *Cassigerinella chipolensis* (Cushman and Ponton)

PLATE 4: FIGURE 16

*Cassidulina chipolensis* Cushman and Ponton, 1932:98, pl. 15: figs. 2a–c.—Jenkins, 1971:73–74, pl. 1: fig. 30.

OCCURRENCE.—Rare specimens of this species are found in the upper beds of the Pungo River Formation in the Lee Creek Mine in North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:377) reported a relatively long range for this species, from zone P18 (early Oligocene) to zone N13 (middle Miocene).

## Genus *Globigerina* d'Orbigny, 1826

REMARKS.—A large variety of species has been placed in this genus by various authors; the primary unifying characteristic is the umbilical position of the aperture. Fleisher (1974:1009–1012, 1018–1019) discussed the modification and splitting of this group. Fleisher's suggestions for different groups within those species assigned to *Globigerina* are based primarily, but not exclusively, upon the nature of the wall, which he felt reflected the phylogeny. Fleisher's concept of *Globigerina*, sensu stricto, would restrict the use of this genus to a fraction of the various species presently placed in the genus. Until more extensive studies are made, however, *Globigerina* will be used for those species that have an umbilical aperture and have traditionally been placed in this genus.

### *Globigerina apertura* Cushman

PLATE 1: FIGURE 10

*Globigerina apertura* Cushman, 1918:57, pl. 12: figs. 8a–c.—Zachariasse, 1975:119–120, pl. 16: figs. 1–2.

*Globigerina bulloides apertura* Cushman.—Blow, 1969:317, pl. 12: fig. 8.

REMARKS.—*Globigerina apertura* is distinguished from *G. bulloides* by a larger, rimmed aperture that is more centrally umbilicate, and by having more appressed chambers and a coarsely cancellate wall (Fleisher, 1974:1019; Zachariasse, 1975). The species was originally described from the Yorktown Formation in Virginia.

OCCURRENCE.—Rare in the Yorktown Formation in outcrops near Suffolk, Virginia, the type area for the species; in the upper part of the sequence exposed along the Meherrin River near Murfreesboro, North Carolina; and in the Norfolk, Virginia, Moores Bridge Well core at a depth of 113 feet (34.4 m). Akers (1972:30) reported it from the Yorktown Formation at Rice's Pit, Hampton, Virginia, and Copeland (1964:281) reported it from Natural Well and Barwick Farm in the Duplin Formation in North Carolina (Figure 1, loc. 9, 20, 21).

STRATIGRAPHIC RANGE.—Blow (1969:317) reported a range from zone N16 to zone N19. Jenkins and Orr (1972:1086) recorded it from the equivalent of zone N18 to the upper part of zone N20.

### *Globigerina euapertura* Jenkins

PLATE 4: FIGURE 15

*Globigerina euapertura* Jenkins, 1960:351, pl. 1: figs. 8a–c; 1971:147, pl. 15: figs. 457–461: pl. 16, fig. 462.—Jenkins and Orr, 1972:1088, pl. 9: figs. 1–6.
*Turborotalia (Turborotalia) euapertura* (Jenkins).—Fleisher, 1974:1035.

OCCURRENCE.—Rare in the Pungo River Formation in the Lee Creek Mine, North Carolina.

STRATIGRAPHIC RANGE.—Jenkins and Orr (1972:1088) recorded a range for this species corresponding to zone P18 to zone N3, and smaller specimens (*G.* cf. *euapertura*) extending to the equivalent of zone N6. Fleisher (1974) reported this species from zone P22 to zone N7–N8; the upper limit is similar to the age of the present occurrence.

### *Globigerina praebulloides pseudociperoensis* Blow

PLATE 1: FIGURES 7–9

*Globigerina praebulloides pseudociperoensis* Blow, 1969:381–382, pl. 17: figs. 8–9.

OCCURRENCE.—Rare to common in bed 10 of the Calvert Formation at Plum Point, Maryland.

STRATIGRAPHIC RANGE.—Blow (1969:321) reported a range from zone N7 to zone N12.

### *Globigerina woodi woodi* Jenkins

PLATE 4: FIGURES 9–11

*Globigerina woodi* Jenkins, 1960:352, pl. 2: figs. 2a–c.
*Globigerina (Globigerina) woodi woodi* Jenkins.—Jenkins, 1971: 159–160, pl. 18: figs. 548–550.

OCCURRENCE.—Rare in the upper part of the Pungo River Formation in the Lee Creek Mine, North Carolina.

STRATIGRAPHIC RANGE.—Jenkins and Orr (1972:1090) reported a range equivalent to zone N4 to zone N17. Kennett (1973:578, 583, 584, 588) recorded its upper limit in the lower Pleistocene, N22.

### *Globigerina* species cf. *G. angulioffícinalis* Blow

PLATE 4: FIGURES 13, 14

REMARKS.—Specimens from the Pungo River Formation are similar to *G. angulioffícinalis* Blow, 1969, in having 4½ chambers in the last whorl, incised intercameral sutures, and a similar appearance of the wall. Pungo River specimens differ in having a narrower and shallower umbilicus and a lower arched aperture. In view of these differences between the Pungo River specimens and those illustrated by Blow, the specimens from the Pungo River are not included within the species, although there appears to be a close relationship.

OCCURRENCE.—Rare in the upper beds of the Pungo River Formation in the Lee Creek Mine, North Carolina.

STRATIGRAPHIC RANGE.—The specimens from

the Pungo River Formation occur in rocks that are assigned to zone N8 on the basis of the co-occurrence of other planktonic species. *G. angulioficinalis*, according to Blow (1969:315), has a range from zone P17 to zone N2 and is thus restricted to the Oligocene.

## Genus *Globigerinatella* Cushman and Stainforth, 1945

### *Globigerinatella insueta* Cushman and Stainforth

PLATE 6: FIGURE 17

*Globigerinatella insueta* Cushman and Stainforth, 1945:69, pl. 13: figs. 7–9.—Blow, 1969:330, pl. 26: figs. 1–7.

REMARKS.—Only a single specimen was found. It has a series of separated bullae and appears to fit within the range of variation described by Brönnimann (1950). It is very similar to the specimen illustrated by Brönnimann and Resig (1971, pl. 21: fig. 1).

OCCURRENCE.—The single specimen was found in the Pungo River Formation in the Norfolk, Virginia, Moores Bridge Well, at a depth of 581 feet (177 m).

STRATIGRAPHIC RANGE.—Blow (1969:330) reported a range from the beginning of zone N6 to the lower part of zone N9.

## Genus *Globigerinita* Brönnimann, 1951

### *Globigerinita glutinata ambitacrena* (Loeblich and Tappan)

PLATE 1: FIGURES 11–13

*Tinophodella ambitacrena* Loeblich and Tappan, 1957:114, figs. 2a–3c.

*Globigerinita glutinata ambitacrena* (Loeblich and Tappan).—Fleisher, 1974:1022, pl. 9: fig. 3.

REMARKS.—Following the usage of Fleisher (1974), which is compatible with my observations on limited material of Miocene to Holocene age, forms with a simple bulla are placed in the "subspecies" *G. glutinata ambitacrena.*

OCCURRENCE.—Rare in the upper part of the Pungo River Formation in the Lee Creek Mine and in the Yorktown Formation in North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:327) reported a range of zone N5 to zone N23.

## Genus *Globigerinoides* Cushman, 1927

### *Globigerinoides altiaperturus* Bolli

PLATE 1: FIGURES 1, 2; PLATE 4: FIGURES 7, 8

*Globigerinoides triloba altiapertura* Bolli, 1957:113, pl. 25: figs. 7a–8.

*Globigerinoides altiaperturus* Bolli.—Jenkins, 1971:174–175, pl. 20: figs. 604–606.

OCCURRENCE.—Rare in the upper part of the Pungo River Formation in the Lee Creek Mine, North Carolina, and in bed 10 of the Calvert Formation, Plum Point, Maryland.

STRATIGRAPHIC RANGE.—Blow (1969:325) reported a range from zone N5 to the lower parts of zone N7. Brönnimann and Resig (1971:1441) recorded a range from zone N4 to zones N7/8, and it appears from this and other works (Fleisher, 1974:1023) that this species ranges into zone N8. The occurrence in bed 10 of the Calvert Formation indicates a range into upper zone N8 or lower zone N9 in this area.

### *Globigerinoides sicanus* de Stefani

PLATE 1: FIGURES 4, 5

*Globigerinoides conglobata* (Brady).—Cushman and Stainforth, 1945:68, pl. 13: fig. 6.

*Globigerinoides sicana* de Stefani, 1952:9.—Fleisher, 1974: 1024, pl. 9: fig. 10.

*Globigerinoides bispherica* Todd, 1954:681, pl. 1: figs. 1a–c.

*Globigerinoides sicanus* de Stefani.—Blow, 1969:326.

OCCURRENCE.—Rare in bed 10 of the Calvert Formation at Plum Point, Maryland.

STRATIGRAPHIC RANGE.—Blow (1969:327) reported that the range was from the beginning of zone N8 to within the lower part of zone N9. Brönnimann and Resig (1971:1251, 1441) recorded it as low as the top of zone N6 in some cores in the Pacific Ocean.

### *Globigerinoides trilobus trilobus* (Reuss)

PLATE 4: FIGURE 12

*Globigerina triloba* Reuss, 1850:374, pl. 47: figs. 11a–d.
*Globigerinoides triloba triloba* (Reuss).—Bolli, 1957:112–113, pl. 25: figs. 2a–c.
*Globigerinoides trilobus trilobus* (Reuss).—Jenkins, 1971:180–182, pl. 19: figs. 571–581.

OCCURRENCE.—Rare to common in the Calvert Formation in Maryland, the Pungo River Formation in Virginia and North Carolina, the Yorktown Formation in Virginia and North Carolina, and the Waccamaw and Croatan formations in North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:326) reported a range from zone N6 to zone N23.

## Genus *Globoquadrina* Finlay, 1947

### *Globoquadrina altispira altispira* (Cushman and Jarvis)

PLATE 2: FIGURES 4, 7, 8

*Globigerina altispira* Cushman and Jarvis, 1936:5, pl. 1: figs. 13a–c, 14.
*Globoquadrina altispira altispira* (Cushman and Jarvis).—Bolli, 1957:111, pl. 24: figs. 7a–8b.—Stainforth et al., 1975:245, fig. 100.

OCCURRENCE.—Rare in bed 10 of the Calvert Formation in Maryland, and in the lower part of the Yorktown Formation along the bluffs of the Meherrin River near Murfreesboro, North Carolina. Dorsey (1948:313, fig. 28) reported rare occurrences in beds 10 to 12 of the Calvert Formation and bed 16 of the Choptank Formation in Maryland.

STRATIGRAPHIC RANGE.—Blow (1969:339) reported a range from zone N4 to the lower part of zone N20 and a probable range in deep oceanic areas into part of zone N21. Upon examination of many land-based sequences, Blow (1969:255) considered this species to have become extinct in the lower part of zone N20 during shallow-water sequences found on the continents. In the deep-ocean sequences sampled by JOIDES, later extinction horizons than early N20 have been found, as mentioned by Blow. In the Pacific, Brönnimann and Resig (1971:1437) recorded this species from the middle of zone N20, Parker (1967:165) and Jenkins and Orr (1972:1094), the lower part of N21, and Kennett (1973:578, 580, 583, 584, 589, 596), the top of N21. In the North Atlantic, Poag (1972b:504, 514) found this species into the lower part of N21.

## Genus *Globorotalia* Cushman, 1927

As discussed by Fleisher (1974:1009–1012, 1025–1026), the genus *Globorotalia* has been used to include a diverse multitude of forms. The general usage of Fleisher is followed here, but not the subgeneric groupings, as there is still a need for lineage studies to demarcate the different stocks clearly.

### *Globorotalia hirsuta hirsuta* (d'Orbigny)

PLATE 3: FIGURES 5–7; PLATE 5: FIGURES 9, 10

*Rotalina hirsuta* d'Orbigny, 1839b:131, pl. 1: figs. 37–39.
*Globorotalia hirsuta hirsuta* (d'Orbigny).—Blow, 1969: 398–400, pl. 8: figs. 1–3, pl. 43: figs. 1–2.

OCCURRENCE.—Rare in the Yorktown Formation in the type area at the cliffs at Yorktown, Virginia, and in the Croatan Formation in the Lee Creek Mine.

STRATIGRAPHIC RANGE.—Blow (1969:363) reported a range from zone N22 to zone N23, and Brönnimann and Resig (1971:1433) recorded this species from the middle of zone N22 into the Holocene. Most other records of older ranges, such as Parker's (1967:178), from the middle of N20 upward, and Jenkins' and Orr's (1972:1099), from N19/20 upward, have to be studied with caution as these authors did not differentiate the subspecies proposed by Blow (1969:398–402).

### *Globorotalia menardii* (Parker, Jones, and Brady)

PLATE 3: FIGURES 1–3

*Rotalia (Rotalie) menardii* d'Orbigny, 1826:273, model no. 10 [nomen nudum].
*Rotalia menardii* Parker, Jones, and Brady, 1865:20, pl. 3: fig. 81.—Banner and Blow, 1960:31–33, pl. 6: figs. 2a–c.

*Globorotalia menardii* (Parker, Jones, and Brady).—Jenkins, 1971:90, pl. 6: figs. 135–137.

REMARKS.—The illustrated specimen and others from this area closely resemble *G. menardii* form 5 of Tjalsma (1971:60, pl. 6, figs. 3a–5c), particularly those specimens referred to this taxon by Zachariasse (1975, pls. 3, 4), although the proximal ends of the intercameral sutures are perpendicular or slightly acute to the spiral suture rather than slightly oblique.

OCCURRENCE.—Rare in the Yorktown Formation in Virginia and North Carolina and in the Duplin Formation in North and South Carolina. Akers (1972:36) reported it from the Waccamaw Formation at Walkers Bluff, North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:359) reported a range from zone N14 to zone N23.

### *Globorotalia merotumida* Blow and Banner

PLATE 6: FIGURES 1–13

*Globorotalia (Globorotalia) merotumida* Blow and Banner, in Banner and Blow, 1965:1352, fig. 1a–c.

REMARKS.—Most specimens in the assemblages have the relatively slow increase in whorl height and uniformly enlarging chambers characteristic of *G. merotumida.* Some specimens, however, have a much greater increase in whorl height and likely fall within the range of variation of *G. plesiotumida.*

OCCURRENCE.—Common to rare in the "Virginia St. Marys" at depths from 131.5 to 138 feet (40 to 42 m) in the Gatesville Well, North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:364) reported a range from just above the base of zone N16 to within zone N18.

### *Globorotalia minima* Akers

PLATE 6: FIGURES 14–16

*Globorotalia cararíensis* (d'Orbigny) var. *minima* Akers, 1955: 659, pl. 65: fig. 3a–d.
*Globorotalia minima* Akers.—Blow, 1959:217–218, pl. 19: figs. 122a–c.

OCCURRENCE.—Common to rare in the Pungo River Formation at depths from 131.5 to 138 feet (40 to 42 m) in the Gatesville Well, North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:352) reported a range from the middle of zone N7 to within zone N13. Brönnimann and Resig (1971:1433, 1441) recorded this species from the lower part of zone N6 to within zone N13.

### *Globorotalia peripheroronda* Blow and Banner

PLATE 5: FIGURES 5, 6

*Globorotalia (Turborotalia) peripheroronda* Blow and Banner, 1966:294, pl. 1: fig. 1a–c, pl. 2: figs. 1–3.

OCCURRENCE. Rare to common in the upper beds of the Pungo River Formation in the Lee Creek Mine in North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:354) reported a range from within zone N6 to within zone N11. Brönnimann and Resig (1971:1441) recorded the species as early as zone N5.

### *Globorotalia puncticulata* (Deshayes)

PLATE 3: FIGURES 9–11; PLATE 5: FIGURES 11, 12

*Globigerina puncticulata* Deshayes, 1832:170.—Banner and Blow, 1960:15–17, pl. 5: fig. 7a–c.
*Globorotalia puncticulata* (Deshayes).—Zachariasse, 1975:114–115, pl. 14: fig. 2a–c.

REMARKS.—The specimens from the lower part of the Yorktown Formation (zone 1 of Mansfield) are well-developed members of this species, as illustrated in Plates 3 and 5. Specimens from the middle part of the Yorktown Formation (zone 2 of Mansfield) approach *Turborotalia inflata* in chamber arrangement and outline of the periphery.

OCCURRENCE.—Specimens occur in the lower part of the Yorktown Formation (zone 1 of Mansfield) along the Meherrin River near Murfreesboro, North Carolina, and in the Lee Creek Mine, North Carolina, and in the middle and upper parts of the Yorktown Formation in Virginia and North Carolina. The species also occurs in the

Duplin and Waccamaw formations in North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:354) reported a range from the upper part of zone N19 through zone N23. However, most later authors found the first appearance essentially at the base of zone N19 (Berggren, 1972:970, 973; Cita and Gartner, 1973:530, 533, 536; Kennett, 1973:587; Gradstein, 1974:68, 99; Zacharriasse, 1975:30–31, 37; Poore and Berggren, 1975:273, 278, 282). The upper limit of the species is uncertain. In the Mediterranean region it disappears within zone N20 (Gradstein, 1974:68, 99; Zacharriasse, 1975:30–31, 37). Kennett (1973:587) marked its extinction in the middle of zone N21 in the Pacific Ocean sequences. Berggren and Amdurer (1973, fig. 10) and Blow (1969:354) found it through zone N23. Poore and Berggren (1975:273, 278) showed an upper limit in the latest Pliocene or earliest Pleistocene (probably equivalent to uppermost N21 or lower N22). Cifelli (pers. comm., 1975) noted that *G. puncticulata*, in the form recognized by the above authors, does not occur today in the plankton in the North Atlantic Ocean, and that forms previosuly placed under that name belong to what is now called *G. crassiformis*. If *G. puncticulata* did become extinct sometime during the Pliocene or early Pleistocene as stated by various authors, then the occurrence of the type suite of Deshayes and d'Orbigny at Rimini (Banner and Blow, 1960:15) requires reclassification of fossil specimens.

### *Globorotalia scitula praescitula* Blow

PLATE 5: FIGURES 1–4

*Globorotalia scitula praescitula* Blow, 1959:221, pl. 19: figs. 128a–c.

*Globorotalia (Turborotalia) scitula praescitula* Blow.—Blow, 1969:356, pl. 4: figs. 21–23, pl. 39: fig. 9.

OCCURRENCE.—Rare to common in the upper part of the Pungo River Formation in the Lee Creek Mine, North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:356) reported the range as zone N5 to near the end of zone N9.

### *Globorotalia* species cf. *G. crassula* Cushman and Stewart

PLATE 3: FIGURES 4, 8, 12

REMARKS.—A single specimen has more chambers in the final whorl than most individuals of *G. crassula*, although Berggren and Amdurer (1973, pl. 30: fig. 9) illustrated *G. crassula* with 4½ chambers in the final whorl. Specimens similar to the one from the Yorktown Formation were figured by Lamb and Beard (1972, pl. 2, figs. 10–12; pl. 20, figs 3–7) as *G. crassacrotonensis* Conato and Follador, a form placed in *G. crassula*, sensu lato, by Berggren and Amdurer (1973:367). Probably the most similar form was illustrated by Rögl (1974, pl. 5, figs. 1–9, 13–15) as *Globorotalia crassaformis* cf. *viola* Blow, 1969. Rögl did not assign his specimens to *G. crassula* because they lack the moderately strong-keel development found in this species.

OCCURRENCE.—A single specimen was found in the lower part of the Yorktown Formation (*Placopecten clintonius* zone of Mansfield) in the bluffs along the Meherrin River near Murfreesboro, North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:361, 362) reported a range from zone N18 to zone N23 for *G. crassula crassula* and *G. crassula viola*.

### *Globorotalia* species cf. *G. truncatulinoides truncatulinoides* (d'Orbigny)

PLATE 5: FIGURES 13–15

REMARKS.—Only a single specimen was found. Blow (1969:405) distinguishes *G. truncatulinoides* from *G. tosaensis* by the presence in the former "of the peripheral carina, no matter where or to what extent it is developed." Blow (1969:395) recognizes *G. truncatulinoides truncatulinoides* "at the first appearance of an 'imperforate' carina regardless of the extent or position of the true carina." Rögl (1974) illustrates transitional forms. By using these criteria, the specimen from the Lee Creek Mine would fall into the range of *G. truncatulinoides truncatulinoides*. The umbilicus is less open than

those of well-developed specimens of *G. truncatulinoides*, and this specimen seems to be an early form of the species. Because only one atypical specimen is known, it is placed in an uncertain status.

OCCURRENCE.—A single specimen was found in the upper part of the Croatan Formation in the Lee Creek Mine, North Carolina. *G. truncatulinoides* was reported by Akers (1972:36) from the Waccamaw Formation at Walkers Bluff, North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:370), Brönnimann and Resig (1971:1248), and Kennett (1973:587 reported a range from the base of zone N22 through zone N23.

## Genus *Orbulina* d'Orbigny, 1839

### *Orbulina universa* d'Orbigny

PLATE 5: FIGURE 8

*Orbulina universa* d'Orbigny, 1839a:3, pl. 1. fig. 1.—Blow, 1956:66, fig. 2, nos. 8–9.—Jenkins, 1971:193–194, pl. 23: fig. 660.—Stainforth et al., 1975:328–330, fig. 150.
*Orbulina cornwallisi* McLean, 1956:365, pl. 53: figs. 3a–b.

REMARKS.—Examination of McLean's type material and additional topotypic material showed no difference in surface appearance between *O. cornwallisi* and *O. universa*.

OCCURRENCE.—Common in the "Virginia St. Marys" beds in the Gatesville Well in North Carolina in the interval from 131.5 to 138 feet (40 to 42 m). Specimens are rare in the Yorktown Formation in Virginia and North Carolina, and in the Duplin and Waccamaw formations in North Carolina. Dorsey (1948:314) found a single specimen in bed 17 of the Choptank Formation in Maryland; examination indicates this specimen should be referred to *O. suturalis*.

STRATIGRAPHIC RANGE.—Blow (1969:334) reported a range from within the lower part of zone N9, through zone N23.

## Genus *Praeorbulina* Olsson, 1964

### *Praeorbulina glomerosa glomerosa* (Blow)

PLATE 1: FIGURES 3, 6

*Globigerinoides glomerosa glomerosa* Blow, 1956:65, fig. 1: nos. 15–19, fig. 2: nos. 1, 2.
*Praeorbulina glomerosa glomerosa* (Blow).—Jenkins, 1971:198, pl. 23: fig. 668.
*Praeorbulina glomerosa* (Blow).—Postuma, 1971:376.—Stainforth et al., 1975:281, fig. 121.

REMARKS.—Stainforth et al. (1975) accepted Postuma's (1971:376) combining of the various subspecies of *P. glomerosa* into one taxon. The relatively few specimens of *Praeorbulina* found in this area indicate that the time of initial appearance of the subspecies is consistent with that found in warmer areas by Blow and that there is a transition upward through the various subspecies similar to that described by Blow.

OCCURRENCE.—A single specimen was found in bed 10 of the Calvert Formation at Plum Point, Maryland. Dorsey (1948:314) reported rare occurrences of *Candorbulina universa* Jedlitschka from beds 11 and 12 of the Calvert Formation in Maryland. Examination of the material indicates that two of the specimens from bed 11 belong in this subspecies, but one from bed 11 and two from bed 12 belong to *P. glomerosa circularis*.

STRATIGRAPHIC RANGE.—Blow (1969:333) reported a range from the middle part of zone N8 to the basal part of zone N9.

### *Praeorbulina glomerosa circularis* (Blow)

PLATE 10: FIGURE 9

*Globigerinoides glomerosa circularis* Blow, 1956:65, fig. 2, nos. 3, 4.
*Praeorbulina glomerosa circularis* (Blow).—Jenkins, 1971:196–197, pl. 23: fig. 665.

REMARKS.—As noted under *P. glomerosa glomerosa*, the lineage proposed by Blow has been questioned. The few specimens found in the Calvert Formation support Blow's interpretation. Bed 10

contains *Globigerinoides sicanus* and *P. glomerosa glomerosa*, bed 11 contains *P. glomerosa glomerosa* and *P. glomerosa circularis*, and bed 12 contains *P. glomerosa circularis*. Although there is overlap in the occurrences, the over-all trend is consistent with Blow's description.

OCCURRENCE.—One specimen was found in bed 11 and two in bed 12 from the collections made by Dorsey from the Calvert Formation in Maryland.

STRATIGRAPHIC RANGE.—Blow (1969:333) reported that its range is from the upper part of zone N8 to near the top of zone N9.

## Genus *Pulleniatina* Cushman, 1927

### *Pulleniatina obliquiloculata obliquiloculata* (Parker and Jones)

PLATE 2: FIGURES 5, 6, 9

*Pullenia obliquiloculata* Parker and Jones, 1865:365, pl. 19: figs. 4a,b.

*Pulleniatina obliquiloculata obliquiloculata* (Parker and Jones).—Banner and Blow, 1967:137–139, pl. 3: figs. 4a–c.

*Pulleniatina obliquiloculata* (Parker and Jones).—Stainforth et al., 1975:385, figs. 186, 187.

REMARKS.—Although these specimens are consistent with the subspecies concept used by Blow in Pliocene and Pleistocene assemblages, they differ slightly from living specimens found in plankton tows and may warrant a separate taxonomic designation to signify their biostratigraphic importance.

OCCURRENCE.—Rare in the uppermost part of the "Yorktown" Formation along the western shore of the Chowan River, at Colerain Landing, Mt. Gould Landing, and Black Rock Landing in Bertie County, North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:376) reported a range from within zone N19 through zone N23, as did Parker (1967:172). Earlier first occurrences are from the beginning of zone N20 (Brönnimann and Resig, 1971:1435) and from zone N22 onward (Kennett, 1973:587).

## Genus *Sphaeroidinellopsis* Banner and Blow, 1959

### *Sphaeroidinellopsis seminulina seminulina* (Schwager)

PLATE 2: FIGURES 10–12; PLATE 5: FIGURE 7

*Globigerina seminulina* Schwager, 1866:256, pl. 7: fig. 112.—Banner and Blow, 1960:24, pl. 7: figs. 2a, b.

*Sphaeroidinella seminulina* (Schwager).—Parker, 1967:161–162, pl. 23: figs. 1–5.

OCCURRENCE.—Rare in the "Virginia St. Marys" beds in the Gatesville Well, North Carolina, at a depth of 131.5 feet (40 m) and in the lower part of the Yorktown Formation (*Placopecten clintonius* zone of Mansfield) along the bluffs of the Meherrin River near Murfreesboro, North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:338) reported a range from zone N6 to near the zones N19/N20 boundary in most localities, with a range possibly as high as the lower part of zone N21 in the deep sea sequences. The youngest range, as indicated by Blow, is variable, depending apparently upon the location and environment. A range to uppermost zone N20 was given by Poag (1972b:492, 493, 499) and Berggren and Amdurer (1973:353, figs. 4, 7, 8) in the Atlantic. A range to the lower part of zone N21 was given by Parker (1967:161), to the latter part of zone N21 by Kennett (1973:587, 591, 594), and into the lower part of zone N22 by Brönnimann and Resig (1971:1435). Berggren and Van Couvering (1974:31) placed the extinction datum in the lowest part of zone N21.

### *Sphaeroidinellopsis subdehiscens subdehiscens* (Blow)

PLATE 2: FIGURES 13–15

*Sphaeroidinella dehiscens subdehiscens* Blow, 1959:195–196, pl. 12: fig. 71a–c, 72.

*Sphaeroidinellopsis subdehiscens subdehiscens* (Blow).—Blow, 1969:338, pl. 30: figs. 1–3, 6.

OCCURRENCE.—A single specimen was found in

the lower part of the Yorktown Formation in the *Placopecten clintonius* zone of Mansfield along the bluffs of the Meherrin River near Murfreesboro, North Carolina. Akers (1972:32) reported this species from the Yorktown Formation at Rice's Pit, Virginia.

STRATIGRAPHIC RANGE.—Blow (1969:338) reported a range from the base of zone N13 to within zone N19. Some workers (e.g., Parker, 1967:160) had a similar latest occurrence, but most recent work shows considerably later occurrences for this species: the top of N19/N20 (Ujiié and Oki, 1974:44), the top of N20 (Brönnimann and Resig, 1971:1435), the lower part of N21 (Poag, 1972b:515; Berggren and Van Couvering, 1974:67), and as recent as the lowest part of N22 (Kennett, 1973:587, 588).

## Genus *Turborotalia* Cushman and Bermudez, 1949

In addition to the type-species *Globorotalia centralis* Cushman and Bermudez and other related species that also occur in Eocene strata, a wide variety of species from Miocene and younger ages have been placed in this genus or subgenus. A problem with Blow's (1969) concept of this genus is that species from several different lineages, which possess characteristics of "*Turborotalia*" during some stage of the lineage development, are placed together, making the genus recognizably polyphyletic. This problem was discussed by Fleisher (1974). Although many workers have used *Turborotalia* for species occurring in Miocene and younger strata, it appears that this name should be restricted to the Eocene lineages, because the phylogenetic gap between these two groups is large. This restriction leaves a large number of younger species without a generic name. *Neogloboquadrina* has been used for "*Turborotalia*" *dutertrei* and its related forms. In this study, species possessing a rounded periphery without an imperforate carina are temporarily placed in "*Turborotalia*" pending resolution of the problem.

### "*Turborotalia*" *birnageae* (Blow), new combination

PLATE 4: FIGURES 1–6

*Globorotalia birnageae* Blow, 1959:210–211, pl. 17: fig. 108a–c.
*Globorotalia* (*turborotalia*) *birnageae* Blow.—Blow, 1969:346, pl. 34: figs. 7, 8.

REMARKS.—The number of chambers in the last whorl varies from approximately 4½ to 5½. The aperture varies in position, becoming more extraumbilical in some specimens, and ranges from a very low slit (Plate 4: figures 2 and 3, and to a lesser degree Plate 4: figure 4) to a somewhat arched aperture (Plate 4: figure 5). The wall texture is coarsely cancellate.

OCCURRENCE.—Rare to common in the upper beds of the Pungo River Formation in the Lee Creek Mine, North Carolina, and rare in the 581 to 618 foot (177 to 188 m) interval in the Norfolk, Virginia, Moores Bridge Well.

STRATIGRAPHIC RANGE.—Blow (1969:346) reported a range from within zone N7 to within the later part of zone N9. Brönnimann and Resig (1971:1441) recorded the species as early as zone N6, with specimens of *G.* aff. *birnageae* specimens in zone N4.

### "*Turborotalia*" *acostaensis humerosa* (Takayanagi and Saito), new combination

PLATE 2: FIGURES 1–3

*Globorotalia humerosa* Takayanagi and Saito, 1962:78, pl. 28: figs, 1–2.—Stainforth et al., 1975:357–360, fig. 170.
*Globorotalia* (*Turborotalia*) *acostaensis humerosa* Takayanagi and Saito.—Blow, 1969:345–346, pl. 33: figs. 4, 5, 7–9, pl. 34: figs. 1–3.

OCCURRENCE.—Rare to common in the lower part of the Yorktown Formation in the *Placopecten clintonius* zone along the bluffs of the Meherrin River near Murfreesboro, North Carolina. Akers (1972:32) reported this species from the Yorktown Formation in Rice's Pit in Virginia and the basal part of the section (*Placopecten clintonius* zone) in the Lee Creek Mine, North Carolina, and in the Waccamaw Formation at Walkers Bluff and Old Dock in North Carolina.

STRATIGRAPHIC RANGE.—Blow (1969:345) reported a range from the latest part of zone N16 through N23. The ranges reported in most subsequent studies generally indicate a later origin and an earlier extinction. Parker (1967:169) gave a range from lower N18 to the top of N21; Brönnimann and Resig (1971:1433) recorded it from the middle of N17 into N23; Jenkins and Orr (1972:1099) had a range from N17 to N22; Poag (1972b:485) recorded it from N19 to the end of N21; and Kennett (1973:580, 583, 584, 588, 591) had a range from the base of N19 to N22.

### *"Turborotalia" inflata* (d'Orbigny), new combination

PLATE 3: FIGURES 13–15

*Globigerina inflata* d'Orbigny, 1839b:134, pl. 2: figs. 7–9.
*Globorotalia (Turborotalia) inflata* (d'Orbigny).—Banner and Blow, 1967:145–146, pl. 4: figs. 1a–c, 11.
*Globorotalia inflata* (d'Orbigny).—Zachariasse, 1975:116, pl. 14: fig. 3a–c.—Stainforth et al., 1975:360, fig. 171.

OCCURRENCE.—A single specimen that undoubtedly belongs to this species was obtained from the Waccamaw Formation at Walkers Bluff on the Cape Fear River, North Carolina. Several specimens placed in *G. puncticulata*, although they show strong transitional characteristics to *G. inflata*, were found in the upper part of the Yorktown and Duplin formations in North Carolina. Akers (1972:36, 42) reported this species from Walkers Bluff and Old Dock in the Waccamaw Formation in North Carolina.

STRATIGRAPHIC RANGE.—Although Blow (1969:350) reported a range from zones N17 through N23, most subsequent work has shown a considerably later initial appearance of the species. Boltovskoy (1974:678, 706) reported *G. inflata* from sediments as old as late Miocene in the Indian Ocean, but, judging from his ensuing discussion, it appears that these were confused with *G. crassaformis*. Bolli (1970:581, 614) and Kennett (1973:587) indicated a range from the equivalent of upper N20 through N23, and Parker (1967:179), Ujiié and Oki (1974:39, 44), and Zachariasse (1975:30–31, 39, 79) had the first occurrence at the base of N21. It seems that an earliest occurrence of uppermost N20 to lower N21 is best documented.

## Genus *Spiroplectammina* Cushman, 1927

### *Spiroplectammina mississippiensis* (Cushman)

PLATE 9: FIGURES 5, 9; PLATE 16: FIGURES 1–3

*Textularia mississippiensis* Cushman, 1922b:90, pl. 14: fig. 4.
*Spiroplectammina mississippiensis* (Cushman).—Dorsey, 1948: 275–276, pl. 27: figs. 3a–4b.
*Spiroplectammina spinosa* Dorsey, 1948:276, pl. 27: figs. 5a, 6b.

DESCRIPTION.—Test elongate, varying in width from 1½ to 3 times as long as wide, tapering uniformly towards the initial end; periphery acute, usually keeled, and keel development, if present, varying from slight to very wide in different populations; chambers planispirally coiled in early portion, consisting of 5 or 6 chambers, later part of test biserial; chambers compressed, with little, if any, increase in inflation of chambers throughout ontogeny; sutures distinct, slightly depressed, varying from straight to slightly curved downward, sutural areas filled with clear shell material that is variable in development from a slight line along the suture to broad bands covering as much as half of the surface of the test; wall finely arenaceous with much cement, giving a smooth finish; aperture a moderately low slit at the base of the inner margin of the last-formed chamber.

REMARKS.—This species is variable, as noted in the description. *S. spinosa* Dorsey was distinguished by its straight, horizontal sutures and spinose projections at the peripheral margin. Spinose projections can be seen on many specimens of *S. mississippiensis* as either the thicker parts of a broken peripheral keel or as the incipient parts of a poorly developed keel. Although the holotype of *S. spinosa* has horizontal sutures, as do specimens in some populations of *S. mississippiensis*, the paratypes have slightly curved sutures. Dorsey reported both *S. spinosa* and *S. mississippiensis* in

the same samples, and it seems clear that *S. spinosa* is just an extreme variation within a population of *S. mississippiensis*.

*Spiroplectammina mississippiensis* can be distinguished from *S. exilis* Dorsey, which occurs in the Choptank Formation, because the latter has a more inflated test with a nonkeeled periphery, the sutures are more strongly curved downwards, and it has a longer and narrower shape.

Occurrence.—Rare to common throughout most of the Calvert Formation in Maryland, ranging from beds 3 to 14, and rare in the Pungo River Formation in the Lee Creek Mine and in the "Virginia St. Marys" beds in the Gatesville Well in North Carolina at a depth of 138 feet (42 m).

Stratigraphic Range.—The first appearance of this species is in strata of Eocene age, ranging geographically from Texas to Virginia. It is common in the Oligocene and questionable in the lowermost Miocene strata of the Gulf Coast region. The occurrences in the Miocene Calvert and Pungo River formations and "Virginia St. Marys" beds are probably the most recent records.

### *Spiroplectammina exilis* Dorsey

Plate 10: figures 1, 2; Plate 16: figures 4, 5

*Spiroplectammina gracilis* Cushman and Cahill, 1933:6, pl. 1: figs. 6, 7.
*Spiroplectammina exilis* Dorsey, 1948:275, pl. 27: figs. 1, 2.

Description.—Test elongate, about 2½ times as long as wide, tapering uniformly towards the initial end; moderately inflated test with subacute to narrowly rounded periphery; chambers planispirally coiled in initial stage, numbering 4 or 5, composing small part of test, later part of test biserial consisting of 16 to 20 chambers; chambers compressed with only slight increase in inflation during ontogeny; sutures distinct, slightly depressed, varying from straight to slightly curved downward, meeting periphery at approximately a 45 degree angle; wall finely arenaceous and containing much cement, giving a smooth finish; aperture a low, narrow slit at base of inner margin of last-formed chamber.

Remarks.—This species is distinguished from *S. mississippiensis* (Cushman) by its more inflated cross-section, nonkeeled periphery, more curved sutures, and generally more elongated shape.

Occurrence.—This species is characteristic of the Choptank Formation in Maryland and northern Virginia. Dorsey (1948) reported an occurrence in bed 24 of the St. Marys Formation along the St. Marys River, but extensive collecting by the author has not yielded any specimens belonging to this genus in those strata.

Stratigraphic Range.—The age range is restricted to the middle Miocene.

## Genus *Textularia* Defrance, 1824

### *Textularia obliqua* Dorsey

Plate 16: figures 8, 9

*Textularia obliqua* Dorsey, 1948:279, pl. 28: figs. 6, 7.

Description.—Test broadly elongate, about 1½ times as long as broad, widest part may be at last pair of chambers or at earlier stage, early portion strongly tapering, later portion almost parallel; test moderately inflated, periphery broadly rounded; 7 to 8 pairs of chambers biserially arranged, early chambers much longer than high, later ones increasing in height; sutures distinct, straight, slightly depressed, forming an angle of approximately 30 degrees with horizontal; wall coarsely arenaceous, smoothly finished; aperture an arched slit at base of inner margin of last formed chamber.

Occurrence.—This species is rare throughout beds 22 to 24 of the St. Marys Formation in Maryland and also is found at one locality in the overlying "Virginia St. Marys."

Stratigraphic Range.—The range is from upper middle to probable lower upper Miocene.

### *Textularia mayori* Cushman

Plate 16: figures 11, 12

*Textularia mayori* Cushman, 1922a: 23, pl. 2: fig. 3.—McLean, 1956:320, pl. 36: figs. 1–3.

Description.—Test broadly elongate, almost

as broad as long, widest part at last pair of chambers, uniformly tapering toward initial end; test moderately compressed throughout, periphery strongly angled with variable number of spines projecting from chamber margins; 7 to 8 pairs of chambers biserially arranged, early chambers longer than high, later ones gradually becoming higher; sutures indistinct, later ones slightly depressed, straight to slightly curved downward; wall finely arenaceous with relatively smooth finish; aperture a low slit at base of indented inner margin of last formed chamber.

REMARKS.—Spinosity ranges from complete absence of spines to long projecting spines. This species is similar to *T. gramen* d'Orbigny, and it is probable that the specimens from the Choptank and St. Marys formations placed in *T. mayori* by Dorsey (1948:278) belong to *T. gramen. Textularia gramen* does not have spines and differs from nonspinose forms of *T. mayori* by having a shorter, broader test, which is more inflated in cross-section.

OCCURRENCE.—Rare to very common throughout the Yorktown Formation in Virginia and North Carolina and in the Waccamaw Formation in North Carolina.

STRATIGRAPHIC RANGE.—From zone N19 to present off the southeastern coast of the United States.

### *Textularia ultima-inflata* Dorsey

PLATE 16: FIGURES 6, 7

*Textularia ultima-inflata* Dorsey, 1948:279, pl. 28: fig. 8a–c.

DESCRIPTION.—Test broadly elongate, about 1½ times as long as broad, widest part at last pair of chambers, strongly tapering toward initial part throughout test; test compressed in early portion, inflated in later; periphery subacute in early portion, broadly rounded in later portion; 7 to 8 pairs of chambers biserially arranged, early chambers much longer than high, later ones gradually becoming higher until last pair is about as high as wide; sutures indistinct, not depressed, curved slightly downward; wall finely to coarsely arenaceous; aperture a low slit at indented base of inner margin of last formed chamber.

OCCURRENCE.—Only in beds 17 to 19 of the Choptank Formation in Maryland.

STRATIGRAPHIC RANGE.—The range is restricted to the middle Miocene.

## Genus *Bolivinopsis* Yakovlev, 1891

### *Bolivinopsis fairhavenensis*, new species

PLATE 20: FIGURES 1–4

*Bolivinopsis curta* Cushman, 1948:220 [not *Spiroplectoides curta* Cushman, 1933]

DESCRIPTION.—Test small, about 3 times as long as broad, early planispiral stage moderately compressed, becoming less compressed through growth with later biserial portion only slightly compressed, being oval in cross-section and having a rounded periphery; sides of test nearly parallel with biserial portion having approximately the same width as planispiral; biserial stage usually straight, but may be slightly to moderately curved; chambers distinct in both stages; 7 to 8 chambers in planispiral stage, usually 3 to 4 slightly inflated chambers of equal height and width in each row of biserial stage; sutures distinct, slightly depressed, forming approximately a 45 degree angle with periphery; wall calcareous, radial, finely perforate, smooth, highly translucent to transparent; an elongate oval aperture in the terminal face extending to the inner margin.

REMARKS.—*Bolivinopsis* is most common in Cretaceous to Eocene rocks; *B. fairhavenensis* is one of the youngest species of the genus. The nature of the wall structure within the genus, as typified by the Russian type-species, remains uncertain. Some species placed in *Bolivinopsis* clearly look agglutinated, while others, including the present species, clearly appear to be perforate calcareous. Some species in the USNM collections that are placed in *Spiroplectammina* Cushman, 1927, also appear to be calcareous perforate. This problem of the generic wall structure is discussed in Loeblich and Tappan (1964:251). Examination of the species in the USNM collections shows three

groups of species that apparently have the same pattern of chamber arrangement. One group has a clearly agglutinated structure, ranging from coarse- to fine-grained; one has clearly calcareous perforate structure and one may be finely agglutinated or calcareous perforate. This last group will have to be sectioned to determine the wall structure. If the type-species of *Bolivinopsis*, *B. capitata* Yakovlev, does prove to have a calcareous perforate wall, as has been suggested, then the calcareous perforate group does have a name. If this species proves to be agglutinated, then it probably should be the senior synonym of *Spiroplectammina*, and the perforate group will need a new generic name.

*Bolivinopsis curta* (Cushman) differs from *B. fairhavenensis* in that it has a broader and more inflated test (about twice as thick) containing more inflated chambers throughout and a more roughened or granular wall texture.

*Bolivinopsis attenuata* (Cushman) from the Eocene of the Atlantic shelf differs by having a broad planispiral stage followed by a narrow biserial stage with compressed chambers, a subacute periphery, and limbate sutures.

Occurrence.—Restricted in outcrop occurrence in Maryland to the top of bed 3 of the Fairhaven Member of the Calvert Formation in Calvert County. The abundance may be as high as 4 percent. Cushman (1948) found it in the lower 100 feet (30 m) of the Calvert Formation in the Hammond Well on the Eastern Shore of Maryland. It also was recorded in the upper 10 feet (3 m) of the Eocene in this well, but this probably represents down-hole contamination. In a continuous core hole at the site of the Baltimore Gas and Electric Company's nuclear power plant near St. Leonards, Calvert County, Maryland, this species occurs from within 8 feet (2.4 m) of the base of the Calvert Formation to the top of bed 3, an interval of 108 feet (33 m). In Maryland, this species is characteristic of the lower part of the Calvert Formation, the Fairhaven Member. The species was found in one sample in the Pungo River Formation in the Lee Creek Mine, North Carolina.

Stratigraphic Range.—The occurrences in Maryland are in the lower part of the Calvert Formation, below the beds assigned to the latest part of planktonic zone N8 or N9. The North Carolina occurrence is in beds dated as probably late N8. Thus, the upper age limit of the species in this area is latest N8 (late early Miocene). Although the lower part of the Calvert Formation appears to be somewhere in zone N8, it has not been dated with certainty; therefore the lower range of this species is still uncertain.

Type Locality.—The type locality for the holotype, figured paratypes, and unfigured paratypes is Randle Cliffs on the western shore of Chesapeake Bay, Calvert County, Maryland, in the upper part of bed 3 of the Calvert Formation.

Types.—The holotype is USNM 252518; figured paratypes are USNM 252519 and 252520; all from USGS 25981.

## Genus *Quinqueloculina* d'Orbigny, 1826

### *Quinqueloculina lamarckiana* d'Orbigny

Plate 17: figures 1, 2, 6

*Quinqueloculina lamarckiana* d'Orbigny, 1839a:189, pl. 11: figs. 14, 15.—Cushman, 1929:26, pl. 2: fig. 6.
*Quinqueloculina venusta*? Cushman, 1918:70, pl. 29: fig. 3a–c.
*Quinqueloculina cuvieriana* Cushman, 1919:69.
*Quinqueloculina seminulangulata* McLean, 1956:322, pl. 37: fig. 8a, b.

Description.—Test about 1½ times as long as wide, triangular in cross-section, periphery acute to subacute; chambers broad and flattened, middle chamber large, projecting, having distinct acute edge, other chambers visible as narrow band; sutures distinct, slightly depressed; surface smooth, polished, covered with few low costae that are parallel to slightly oblique to periphery; aperture oval, having a slightly thickened rim and a short, stout tooth.

Remarks.—The degree of acuteness of the periphery varies from strongly angulated to subangulated. The strength of the ornamentation varies from barely visible on the early chambers to well

developed on all chambers. These characters vary with latitude in living populations along the Atlantic Coast of the United States. Specimens with a more rounded periphery and less-developed costae occur in the northern part of the range in coastal waters off North Carolina, whereas forms having a more angular periphery and more strongly developed costae are more abundant in populations off Florida. A similar north-to-south pattern in the variation is seen in the Yorktown and Waccamaw formations; the more southern localities have more strongly angulated and ornamented specimens.

OCCURRENCE.—Rare to common throughout the Yorktown Formation in Virginia and North Carolina and in the Waccamaw Formation in North and South Carolina.

STRATIGRAPHIC RANGE.—The range in this area is from lower Pliocene strata (zone N19) into the living fauna. In South America, the West Indies, and the southern United States, reports extend its range to the Eocene.

## Genus *Massilina* Schlumberger, 1893

### *Massilina glutinosa* Cushman and Cahill

PLATE 17: FIGURES 3, 4, 7

*Massilina glutinosa* Cushman and Cahill, 1933:10, pl. 2: fig. 10a–c.—Dorsey, 1948:281, pl. 29: fig. 6a–c.

DESCRIPTION.—Test strongly compressed with parallel sides, periphery broadly rounded, test oval in outline, apertural end not projecting; chambers of uniform width, later chambers nearly circular in cross-section; sutures distinct, slightly depressed; wall agglutinated with much cement; aperture circular and has slightly thickened lip, containing bifid tooth that may be thin and elongated or short and stout.

OCCURRENCE.—Known from beds 16 through 20 of the Choptank Formation in Maryland and northern Virginia.

STRATIGRAPHIC RANGE.—Restricted to the middle Miocene.

### *Massilina marylandica* Cushman and Cahill

PLATE 16: FIGURES 10, 13, 14

*Massilina marylandica* Cushman and Cahill, 1933:10, pl. 2: fig. 9a–c.

DESCRIPTION.—Test strongly compressed, periphery rounded, test oval in outline, apertural end not projecting; chambers distinct, later ones increasing considerably in width; sutures distinct, slightly depressed; wall has well-developed longitudinal costae crossing chamber at slight angle to the periphery; aperture circular, containing thickened bifid tooth.

OCCURRENCE.—Found only in the upper part of the St. Marys Formation at Langley's Bluff and Chancellor Point, Maryland.

STRATIGRAPHIC RANGE.—Middle to lower upper Miocene.

## Genus *Nodosaria* Lamarck, 1812

### *Nodosaria catesbyi* d'Orbigny

PLATE 11: FIGURES 5, 6; PLATE 17: FIGURE 11

*Nodosaria catesbyi* d'Orbigny, 1839a:16, pl. 11: figs. 8–10.—McLean, 1956:329, pl. 39: figs. 1–4.

DESCRIPTION.—Test elongate, varying from slightly tapering to slightly expanding; initial end blunt and rounded, some specimens have an apical spine; chambers vary in number from 2 to 4; sutures distinct, depressed; wall ornamented by 12 to 16, high, sharp, longitudinal costae, continuous across the sutures; aperture terminal, radiate on short to medium neck; wall calcareous, finely perforate.

REMARKS.—Originally characterized by d'Orbigny as composed of two chambers; specimens having three or four chambers occur in the present material. The later chambers may be as large or larger than the earlier, or considerably smaller in size. The costae vary in development from strong to very faint or absent on the last chamber. The costae may continue onto the neck where they are twisted.

OCCURRENCE.—Lower and middle parts of the Yorktown Formation in Virginia and northern North Carolina.

STRATIGRAPHIC RANGE.—The occurrences in this area are restricted to the lower and middle Pliocene parts of the Yorktown Formation, although the species is found in upper Oligocene and Pliocene strata in other areas.

## Genus *Bolivina* d'Orbigny, 1839

REMARKS.—Loeblich and Tappan (1964:549) confine the usage of *Bolivina* to those forms having the test "somewhat compressed . . . basal margins of chambers with retral processes or backward directed chamber overlap . . . . Species without chamber overlaps, commonly keeled and strongly compressed, are placed by us in *Brizalina*."

These distinctions have not been uniformly applied by subsequent authors. *Bolivina pungoensis*, new species, undoubtedly belong to the genus *Bolivina* under these concepts, but the placement of *B. calvertensis* would be more difficult as it is transitional between the groups. The gradational nature of the large number of species belonging to the *Bolivina-Brizalina* complex as interpreted by Loeblich and Tappan makes placement of the species difficult.

### *Bolivina calvertensis* Dorsey

PLATE 9: FIGURES 1–4

*Bolivina calvertensis* Dorsey, 1948:306, pl. 36: fig. 17a–c.

DESCRIPTION.—Test elongate, from 2 to 3 times as long as broad, gently tapering toward both ends and having greatest width at or slightly anterior to mid-point of test; somewhat compressed test that has subacute periphery in earlier stages, becoming more inflated with more rounded periphery in later stages; chambers in later part moderately distinct, slightly inflated; sutures somewhat distinct with inner part being curved and later straight, forming angle of about 30 to 45 degrees with the horizontal; in earlier part, chambers and sutures largely obscured by ornamentation; wall moderately perforate; surface of all but the last 2 or 3 chambers prominently ornamented by closely spaced longitudinal costae, varying in strength from fine to moderately coarse between specimens, numbering approximately 12 to 20, costae may bifurcate and shortly rejoin; aperture moderately narrow, an elongate oval, opening above the base of last formed chamber, sometimes with slight lip.

REMARKS.—Dorsey compared this species to *B. marginata multicostata* Cushman; the latter differs in being much larger, having a more compressed test with a keel, and having fewer costae that are straighter and cover less of the test.

OCCURRENCE.—Dorsey reported the species as rare in beds 6 through 14 in the Calvert Formation in Maryland. Additional collecting by the author also yielded few specimens in bed 5, giving a range from the middle to upper parts of the Calvert Formation. Occurrence is rare to common in the upper part of the Pungo River Formation in the Lee Creek Mine.

STRATIGRAPHIC RANGE.—Found only in those parts of the Calvert and Pungo River formations regarded as equivalent to zones N8–lower N9.

### *Bolivina pungoensis*, new species

PLATE 8

DESCRIPTION.—Test elongate, about 2 to 2½ times as long as broad, gently tapering toward both ends, greatest width near anterior end, usually across base of shoulders of last two chambers; moderately compressed test with subacute periphery in early part, becoming more inflated with more rounded periphery in later two-thirds to one-half of test; chambers distinct, moderately compressed in early stages, becoming more inflated in later part, chambers in early portion low and broad, later increasing considerably in height, inner basal part of chambers extending as a lobe over earlier chambers and the lobular projections becoming very pronounced in later chambers; sutures distinct, depressed, curved near periphery at 50 to 60 degree angle to the horizontal; wall distinctly perforate except for areas surrounding the apertural face; imperforate areas

around aperture generally only partially covered by succeeding chambers in earlier part of the test, more commonly completely overlapped in later parts; aperture narrow, elongate, opening on or near the base of the inner margin of the last-formed chamber, usually with tooth plate exposed.

Remarks.—The apertural face and surrounding area is imperforate, and during ontogeny the amount of imperforate area covered by succeeding chambers varies. In the earlier parts of the test much of the imperforate area remains visible after succeeding chambers are formed (Plate 8: figure 5), whereas during later stages of ontogeny the amount of imperforate area exposed becomes considerably reduced (Plate 8: figure 4), and in the latest stages, only very thin areas, if any, are visible (Plate 8: figure 3).

The grain size within the imperforate area is coarsest in the early stages (Plate 8: figure 9) and becomes increasingly finer in the later stages (Plate 8: figures 7, 8). This appears to be a result of the organism's activity and not of diagenetic alteration, as the same pattern of changing grain size is observable on all specimens. Diagenetic alteration should affect the areas equally as far as regrowth of crystal size is concerned.

A group of species of *Bolivina* appears in the early and lower middle Miocene that seems to be morphologically related, and occurs over much of North America. Although some of the species are apparently restricted stratigraphically, others range well into and through the later parts of the Miocene strata. This group includes *B. pungoensis*, new species, and the following three closely related species, among others.

*Bolivina advena* Cushman (1925:29), described from the Monterey shale of California, differs from *B. pungoensis* by having the lobular extensions not as strongly developed, and by lacking the imperforate areas in the earlier chambers.

*Bolivina floridana* Cushman (1918:49), described from the Choctawhatchee Formation in Florida, is longer and narrower (specimens being 3 to 4 times as long as wide), has the inflation of the chambers beginning much earlier, has a more rounded periphery in the later chambers, has multiple lobular extensions, and lacks the imperforate areas on earlier chambers. *B. floridana imporcata* Cushman and Renz and *B. floridana regularis* Cushman and Renz, from the Miocene of Venezuela, are similar to *B. pungoensis* in the overall shape of the test, but differ in the presence of multiple lobular extensions.

*Bolivina plicatella mera* Cushman and Ponton (1932:82), from the Oak Grove Formation in Florida, differs in having the greatest width at the apertural end, giving a square appearance, having a more compressed test, and lacking the imperforate areas.

Occurrence.—*Bolivina pungoensis* comprises about 3 percent of the foraminiferal assemblages in most samples of the Pungo River Formation in the Lee Creek Mine. It is found also in the Pungo River Formation in the 581 to 616 foot (177 to 187.7 m) interval of the Norfolk, Virginia, Moores Bridge Well.

Stratigraphic Range.—Found only in the parts of the Pungo River Formation that are assigned to planktonic zone N8 of Blow (1969:289) of late early Miocene age.

Type-Locality.—The locality for the holotype and figured paratypes is the Lee Creek Mine, North Carolina, in the upper part of the Pungo River Formation. Unfigured paratypes are from the Moores Bridge Well, Norfolk, Virginia, at depths of 581 and 610 feet (177 and 186 m).

Types.—The holotype is USNM 240134 from USGS locality 26013; figured paratypes are USNM 240135 from USGS locality 26014 and USNM 240136 from USGS locality 26013. Unfigured paratypes are USNM 240151 from USGS locality 26002 and USNM 240152 from USGS locality 26003.

### *Bolivina marginata multicostata* Cushman

Plate 11: figures 1, 2; Plate 17: figures 5, 8

*Bolivina aenariensis* var. *multicostata* Cushman, 1918:48, pl. 10: fig. 2.

*Bolivina marginata* var. *multicostata* Cushman.—Cushman, 1937:87, pl. 10: figs. 71–10.

*Bolivina marginata multicostata* Cushman.—Puri, 1953:121, pl. 22: figs. 3–6.

DESCRIPTION.—Test elongate, about 2½ times as long as broad, uniformly tapering toward initial end, very compressed, variable development of keel on periphery ranging from prominent to almost absent, commonly absent on last several chambers; approximately 18 to 20 compressed chambers, early ones low and broad, later ones increasing in relative height; sutures distinct, slightly limbate and curved, intersecting margin at 45 to 60 degree angle; ornamented by a series of longitudinal costae, approximately 6 in number, which vary in strength and extent; may have short basal spine; aperture narrow, elongate, opening at inner margin of base of last formed chamber; wall moderately perforate.

REMARKS.—This species is variable in development of the keel and costae and in the shape of the sutures. The keel may extend along the entire periphery, most of the periphery except for the last two pairs of chambers, or a lesser distance. The costae vary in their length and strength, and in some specimens the central costae may be enlarged to form a median ridge. The shape of the sutures varies from strongly arched to straight. Although both this subspecies and *B. marginata marginata* Cushman occur in the same strata in Florida (Puri, 1953), *B. marginata multicostata* is by far the more common of the two in Virginia and North Carolina.

OCCURRENCE.—Rare in the middle part of the Yorktown Formation in Virginia and North Carolina and at Barwick Farm in the Duplin Formation in North Carolina. Cushman (1937) reported this subspecies from the Calvert Formation in Maryland, but none were found in outcrops of the Calvert Formation during this study. Specimens are found, however, in the subsurface strata of the Pungo River Formation in the Moores Bridge Well at 610 feet (186 m), Norfolk, Virginia.

STRATIGRAPHIC RANGE.—The range in this study area is from uppermost lower Miocene (equivalent to zone N8) to probable middle Pliocene.

## Genus *Hopkinsina* Howe and Wallace, 1932

### *Hopkinsina bononiensis* (Fornasini)

PLATE 11: FIGURES 3, 4

*Uvigerina bononiensis* Fornasini, 1888:48, pl. 3: figs. 12–12a.
*Hopkinsina bononiensis* (Fornasini).—Marks, 1952:288, pl. 1: fig. 25.

DESCRIPTION.—Test elongate, fusiform, initial end rounded; slightly inflated chambers arranged triserially in early stages, later becoming biserial; chambers have lobulate projections over earlier chambers; sutures distinct, depressed; approximately 20 costae of medium strength on each chamber, some bifurcating, others discontinuous, costae do not extend over the sutures; aperture terminal, rounded, on short, relatively broad neck containing slight lip and internal tooth plate; wall calcareous, finely perforate.

REMARKS.—The occurrence in the Pungo River Formation in North Carolina is the first report of this species in North America. The species is widespread in middle Miocene through Pliocene strata of Europe and North Africa, particularly in the Mediterranean region.

Several varieties and subspecies of *H. bononiensis* have been described, but comparative material is lacking in the USNM collections and some of the original illustrations are inadequate for subspecific discrimination of the North Carolina material. The North Carolina specimens appear to be most similar to the original material of Fornasini.

The only species similar to *H. bononiensis* is *H. quasistriata* Krasheninnikov, 1961, from the middle Miocene of Russia, which differs in having barely discernible, very fine longitudinal striae.

OCCURRENCE.—Only in the younger, subsurface part of the "Virginia St. Marys" beds in the Gatesville Well, North Carolina, at a depth of 131.5 to 132 feet (40.1 to 40.2 m).

STRATIGRAPHIC RANGE.—The known range in this area is restricted to the upper Miocene.

## Genus *Sagrina* d'Orbigny, 1839

### *Sagrina pulchella primitiva* (Cushman), new combination

PLATE 17: FIGURES 9, 10

*Bolivina pulchella* var. *primitiva* Cushman, 1930:47, pl. 8: figs. 12a–b.

*Bolivina pulchella primitiva* Cushman.—Puri, 1953:122, pl. 21: figs. 11–12.

DESCRIPTION.—Test about 1½ times as long as broad, greatest breadth formed by last pair of chambers, periphery broadly rounded, lobulate; chambers distinct, inflated, increasing gradually in size, early and middle stages of test triserial, only last 3 chambers biserial; sutures distinct, depressed, straight, making angle of 20 to 30 degrees with horizontal; test ornamented by short, strong, longitudinal costae, usually not crossing sutures; aperture an elongate oval with distinct lip; wall coarsely perforate.

OCCURRENCE.—Rare in the Waccamaw Formation in southern North Carolina. Its distribution elsewhere includes the Pliocene, Pleistocene, and Holocene of Florida and adjacent areas.

STRATIGRAPHIC RANGE.—In the study area the species has a range of upper Pliocene to lower Pleistocene, although it ranges from lower Pliocene into the Holocene in Florida and other southern areas.

## Genus *Siphogenerina* Schlumberger, 1882

### *Siphogenerina lamellata* Cushman

PLATE 9: FIGURES 6, 10–16; PLATE 17: FIGURE 13

*Siphogenerina lamellata* Cushman, 1918:55–56, pl. 12: fig. 3.—Dorsey, 1948:309, pl. 36: figs. 13a, b.

*Siphogenerina spinosa* (Bagg).—Cushman, 1926:10.—Dorsey, 1948:309, pl. 36: figs. 14a, b.

DESCRIPTION.—Test elongate, about 3 to 4 times as long as wide, greatest width at or near apertural end, tapering gradually toward initial end and tapering to broadly rounded at apertural end; early portion triserial, later and greater portion of test uniserial, commonly with 6 to 8 uniserial chambers; chambers distinct, increasing very gradually in size as added, slightly inflated; ornamentation consisting of longitudinal costae, ranging in number from approximately 7 to 9, equally spaced, varying in strength from slightly raised to broadly flanged, and extending the length of the uniserial stage and commonly onto the initial chambers where they may project as basal spines, additional costae seldom added by intercalation; sutures distinct, flush to strongly depressed with a U-shaped pattern, being strongly curved downwards at the costae and arched upwards between costae; aperture terminal with a short cylindrical neck and lip.

REMARKS.—This species appears to have relatively consistent variations over its broad geographic range. The test usually expands toward the apertural end where the greatest width occurs. Less frequently the greatest width may be about two-thirds of the distance from the initial end, with a gradual taper towards the apertural end similar to the shape of *S. collomi* Cushman. A few specimens in the Caribbean region may have additional costae added in the later stages of the test by intercalation (the holotype from Florida has a very slight added costa over the last several chambers), but this characteristic is rare in this species in contrast to other species of *Siphogenerina*.

Basal spines are commonly found in a small to moderate proportion of the population in various geographical areas. The spines are a result of the projection of the basal portion of the costae beyond the initial chambers of the test.

The only other reported species of *Siphogenerina* from the Miocene of the middle Atlantic Coastal Plain is *S. spinosa* (Bagg), originally described from the Choptank Formation at Jones Wharf, Maryland. The type material of this species is not in the Cushman Collection at the Smithsonian and its whereabouts is unknown. The type illustration of *S. spinosa* does not show the basal spines that are discussed in the description and indicated by the species name [although Bagg (1904:480) mentioned distal spines, he probably meant spines at the basal or proximal end]. Basal spines

are prominent in specimens such as Dorsey's from the Calvert Formation and in some specimens from the type area in the Red Bay Formation of Puri and Vernon (1964) in western Florida, and are probably just part of the range of variation within *S. lamellata*. The prominent intercalated costae shown in the type illustration of *S. spinosa* distinguish it from most specimens of *S. lamellata*, but it is probable that both taxa are variants of one species. If so, *S. spinosa* has priority. No other specimens of *Siphogenerina* have been reported from the Choptank Formation, including samples from Jones Wharf examined by Dorsey (1948) and Gibson (1962). Because of the absence of any type material of *S. spinosa*, the two species are not placed in synonymy.

Several related species are found in Miocene strata in Florida, the Caribbean region, and California. Among the most closely related are the following species.

*Siphogenerina transversa* Cushman is very similar to *S. lamellata*, but differs in having a less tapered test; more inflated later chambers, which may give a slightly nodular appearance; more costae (11 to 12 being common); and intercalation and bifurcation of the costae.

*Siphogenerina reedi* Cushman is broader; not as tapered toward the initial end, and has more costae (13), which are more closely spaced and not as strongly developed.

Some specimens of *S. senni* Cushman and Renz closely approach *S. lamellata*, but the former typically differs in having 9 costae that become less strongly developed during ontogeny; commonly having intercalation of costae, a spinose projection at the base of the test (typically better developed than in *S. lamellata*), sutures not as strongly recurved, and very little taper toward the initial end.

*Siphogenerina collomi* Cushman differs in commonly having intercalated costae half-way up the side of the test, having more costae (12–14), and in tapering anteriorly. Broken specimens more closely resemble *S. lamellata*, but have more costae that are not as strongly developed.

Occurrence.—Rare in the Calvert Formation in Maryland in beds 9 to 13; rare in the upper beds of the Pungo River Formation in the Lee Creek Mine, and rare to common in the Norfolk, Virginia, Moores Bridge Well at a depth of 610 feet (186 m) and in the "Virginia St. Marys" beds in the Gatesville Well, North Carolina, at 131.5 feet (40 m). McLean (1956:350) reported one specimen which he attributed to reworking in the Yorktown Formation in Virginia.

Stratigraphic Range.—Specimens are found in the Calvert and Pungo River formations in levels assigned to zones N8 to N11. In the middle Atlantic Coastal Plain this species appears to be useful as an index to strata of this age. Younger ages for this species are reported in other areas. In Florida, the species occurs only in the *Arca* zone (Cushman and Ponton, 1932:86), which provisionally has been placed by Akers (1972:5, 14) in zone N17. Blow (1959:153) found the species to range throughout the Miocene section in Venezuela, which in that area included a range from zone N5 into zone N17; Blow (1959:153) cited the local environment as a possible causal factor for the upper range.

Other closely related species, particularly those found in California, occur through approximately the same time range as *S. lamellata* in North Carolina to Maryland. *Siphogenerina collomi* and *S. reedi* have ranges of zones N8–N9 in California (Kleinpell, 1938:300, 304; Berggren and Van Couvering, 1974, fig. 1), with *S. transversa* being found earlier in approximately zones N1 to N7, and thus being a likely forerunner of this group. In Venezuela, Blow (1959:153) reported a time range of zones N6 to N12 for *S. senni* and zones N6 to N10 for *S. transversa.*

### *Siphogenerina* species

Plate 9: figures 7, 8

Remarks.—Some specimens from the upper beds of the Pungo River Formation in the Lee Creek Mine differ from *S. lamellata* in having almost horizontal sutures and in having twelve moderately developed costae. These specimens probably represent a new species because none of

the other described species of *Siphogenerina* includes such forms.

Occurrence.—Rare in the upper part of the Pungo River Formation in the Lee Creek Mine, North Carolina.

Stratigraphic Range.—The only occurrence of this species is in beds assigned to zone N8.

## Genus *Rotorbinella* Bandy, 1944

### *Rotorbinella bassleri* (Cushman and Cahill), new combination

Plate 18: figures 4–6

*Rotalia bassleri* Cushman and Cahill, 1933:30, pl. 10, fig. 7a–c.—Dorsey, 1948:312, pl. 37: fig. 8a–c.

Description.—Test trochoid, planoconvex, spiral side moderately convex with thickening of shell material at apex, umbilical side varies from slightly convex to slightly concave, outline circular; last several chambers may be lobulate; periphery subacute and limbate; umbilicus depressed with stout plug of clear shell material; 3½ whorls, 20 to 25 chambers, 6 to 7 chambers in last whorl, increasing gradually in size; sutures distinct, strongly recurved and slightly limbate on spiral side, moderately recurved and depressed on umbilical side; aperture an elongate slit with slight lip, extending from near periphery to umbilical plug, apertural slits on last 2 to 4 chambers may be visible; wall coarsely perforate.

Remarks.—The convexity of the test is variable. The spiral side is usually moderately convex, but the umbilical side can vary from concave to convex. In some specimens the last chamber is strongly inflated. This species is similar to *R. colliculus* Bandy and *R. campanulata* (Galloway and Wissler) and clearly belongs to *Rotorbinella* as emended by Douglass and Sliter (1965).

Occurrence.—Rare throughout the Calvert, Choptank, and St. Marys formations in Maryland. A single specimen was found in the lower part of the Yorktown Formation in Virginia.

Stratigraphic Range.—The range is from uppermost lower Miocene (zone N8) to lower Pliocene (zone N19); however, all occurrences except for one specimen are pre-Pliocene.

## Genus *Epistominella* Husezima and Maruhasi, 1944

### *Epistominella danvillensis* (Howe and Wallace)

Plate 20: figures 10–12; Plate 21: figures 9–13

*Pulvinulinella danvillensis* Howe and Wallace, 1932:71, pl. 13: fig. 7a–c.

*Epistominella pontoni* sensu Schnitker, 1970:72–73, pl. 6: fig. 5a–c.

Description.—Test trochospiral, small, approximately equally biconvex with spiral side usually more convex, circular in outline, very slightly lobulate, periphery rounded, umbilical area not depressed, but small clear shell area present where sutures converge in center; 2½ whorls, 20 to 26 chambers, 8 to 10 in last whorl, chambers slightly inflated, gradually increasing in size, last chamber may project above general umbilical surface; sutures distinct, straight to slightly curved and strongly oblique to periphery and slightly limbate on spiral side, umbilical sutures radial to slightly recurved in later chambers, essentially radial in earlier chambers and slightly limbate; aperture a narrow opening parallel to the periphery of the test; wall finely perforate with pores located in center of surface granules.

Remarks.—This species was described from upper Eocene strata in Louisiana. Subsequent records in Eocene strata are from Georgia (McBean Formation) and Virginia (Chickahominy Formation). *Epistominella danvillensis* is reported from Oligocene and lower Miocene strata of Europe; but the illustrations show specimens differing from the paratypes of *E. danvillensis*, and it is doubtful that they are conspecific. Four paratypes of *E. danvillensis* are in the USNM collections, and the present material from the Yorktown and Pungo River formations falls well within the range of morphologic variation of these specimens.

*Epistominella pontoni* (Cushman) is a similar species from strata of Miocene and Pliocene age in northwestern Florida (Plate 21: figures 7, 8). It is characterized by having 6 to 7 inflated chambers in the last whorl, depressed, nonlimbate sutures on both the spiral and umbilical sides, lobulate periphery, and a depressed umbilicus. *Epistominella danvillensis* has less convexity on the umbilical side; lacks a depressed umbilicus; has more limbate sutures on the umbilical side and undepressed sutures on the spiral side; has fewer and more compressed chambers in the last whorl; and a less lobulate periphery.

*Epistominella danvillensis* differs from *E. pungoensis*, new species, by having more chambers in the last whorl, a less lobulate periphery, less limbate sutures, and an imperforate umbilical area.

Occurrence.—This species composes less than 1 percent of the assemblage in the lower and middle parts of the Yorktown Formation in Virginia and North Carolina and in one sample from the Pungo River Formation in North Carolina; however, in the Yorktown Formation in the Lee Creek Mine in North Carolina it composes as much as 9 percent of the assemblage. The occurrences appear to be in strata and areas representing greater water depths in the Yorktown and Pungo River formations.

Stratigraphic Range.—The occurrences in the Pungo River and lower and middle parts of the Yorktown formations give a documented range of upper lower Miocene (zone N8) to possibly middle Pliocene (zones N20–N21), in addition to the Eocene range of the species in the Gulf Coast.

### *Epistominella pungoensis*, new species

Plate 20: figures 13–15; Plate 21: figures 1–6

Description.—Test trochospiral, small, biconvex with spiral side slightly to considerably more convex, circular to slightly oval in outline, slightly to moderately lobulate, periphery rounded, umbilical area flush to slightly depressed, containing moderate to large area of imperforate clear shell material from coalescing of limbate sutures; 3 whorls, 22 to 26 chambers, 6 to 7 in last whorl, chamber slightly inflated, gradually increasing in size; sutures distinct, slightly limbate and straight to slightly curved and strongly oblique to periphery on spiral side, radial and moderately to strongly limbate on umbilical side; aperture a moderately wide slit parallel to the periphery of the test; wall coarsely perforate.

Remarks.—This species is characterized by having 6 to 7 chambers in the last whorl and moderately to strongly limbate sutures on the umbilical side with a large area of imperforate shell material in the umbilical region.

*Epistominella pungoensis* differs from *E. danvillensis* (Howe and Wallace) by having fewer and wider chambers in the last whorl (6 to 7 compared with 8 to 10), a more lobulate periphery, more strongly limbate sutures on the umbilical side, a larger area of imperforate shell material in the umbilical region, and possibly a slightly depressed umbilicus.

*Epistominella pontoni* (Cushman) differs in having more inflated chambers, less limbate sutures on the umbilical side, and lacking the imperforate shell material in the umbilical area.

Occurrence.—The species is common (approximately 8 percent) in the Pungo River Formation in southeastern Virginia in the Norfolk Moores Bridge Well at depths of 581 to 616 feet (177 to 187.7 m) and in the upper part of bed 3 of the Fairhaven Member of the Calvert Formation at Randle Cliffs, Maryland, along the Chesapeake Bay.

Stratigraphic Range.—The range is uppermost lower Miocene (zone N8) to lower middle Miocene (zone N9).

Type-Locality.—The type-locality for the holotype and figured and unfigured paratypes is from a core sample at 610 foot (186 m) depth in the Norfolk, Virginia, Moores Bridge Well.

Types.—The holotype is USNM 252521; figured paratypes are USNM 252522–252525; 10 unfigured paratypes are USNM 252526; all of which are from USGS locality 26003.

## Genus *Rosalina* d'Orbigny, 1826

### *Rosalina cavernata* (Dorsey)

PLATE 10: FIGURE 4; PLATE 17: FIGURES 14–16

*Discorbis cavernata* Dorsey, 1948:311, pl. 37: fig. 2a–c.

DESCRIPTION.—Test planoconvex, spiral side of low convexity with all chambers visible, umbilical side with large cavernous depression containing large bulbous growths on broad chamber flaps, test oval in outline, periphery narrowly rounded; 5 to 6 chambers in last whorl, increasing rapidly in size; sutures distinct, slightly depressed, strongly recurved on spiral side, less recurved and slightly limbate on umbilical side; aperture a low slit under plate-like extension of last chamber, extending to periphery, previous apertures sometimes visible; wall coarsely perforate with a brown chitinous inner lining.

DISCUSSION.—The presence of a relatively open umbilicus, broad chamber flaps, and occasional remnants of earlier apertures places this species in *Rosalina* d'Orbigny as interpreted by Loeblich and Tappan (1964:584).

OCCURRENCE.—Rare throughout the Plum Point Marl Member of the Calvert Formation in Maryland and in the lower part of the Calvert Formation in the Hammond Well on the Eastern Shore of Maryland.

STRATIGRAPHIC RANGE.—The range is uppermost lower to lower middle Miocene (zones N8 to N9).

## Genus *Cancris* Montfort, 1808

### *Cancris sagra* (d'Orbigny)

PLATE 18: FIGURES 1–3

*Rotalina sagra* d'Orbigny, 1839a:77, pl. 5: figs. 13–15.
*Cancris sagra* (d'Orbigny).—McLean, 1956:359, pl. 48: figs. 3–5, 7.

DESCRIPTION.—Test trochospiral, biconvex, moderately elongated to almost oval in outline; 6 to 7 chambers in last whorl, moderately compressed to highly inflated, rapidly enlarging; periphery broadly rounded to moderately compressed with keel, entire or lobulate; umbilical aperture a low slit under broad lip, which may extend over much of umbilicus; wall finely perforate.

OCCURRENCE.—This species is common to rare in most samples of the Yorktown, Duplin, and Waccamaw formations in Virginia and North Carolina.

STRATIGRAPHIC RANGE.—The range is lowest Pliocene, zone N19, into the modern fauna.

## Genus *Elphidium* Montfort, 1808

REMARKS.—Because of the presence of areal openings on the septal face, several workers suggested that the following new species be placed in *Cribroelphidium*. The other features of the test, however, show a close relationship to the type-species and related species of *Elphidium*. In addition, examination of another species of *Elphidium* from the Croatan Formation in the Lee Creek Mine reveals that specimens of undoubtedly a single species range from forms with a row of 3 or 4 openings at the base of the septal face to forms having both basal and areal openings. The character of the aperture alone, therefore, is not considered sufficient justification to place such closely related species in different genera. This view is also stated in Loeblich and Tappan (1964:637): "Some species previously placed in *Cribroelphidium* by reason of the presence of a multiple areal aperture belong to *Elphidium*, as shown by the presence of retral processes and a complex canal system. . . ." In addition, Loeblich and Tappan (1964:632), in the description of *Elphidium*, stated that the "aperture consist[s] of row of pores at base of septal face, earlier septa may also have areal foramina due to resorption." The illustrated specimens in the following species have a broken last chamber, exposing the previous septal face, and this may be the cause for the exposed face showing areal apertures.

### *Elphidium neocrespinae*, new species

PLATES 7, 19: FIGURES 3, 4

DESCRIPTION.—Test free, planispiral, involute, much compressed, sides flattened, nearly parallel; periphery subacute with a broadly rounded keel; umbilical regions flattened, not excavated, containing a variable number of small bosses; chambers usually distinct, although in earlier parts of last whorl sutures may be partially obscured by development of retral processes; number of chambers in final whorl variable from about 10 to 15, chambers relatively narrow and curved; sutures distinct, slightly elevated, strongly curved; retral processes distinct, numbering 11 to 15 in the later chambers, covering much of the surface of the chamber, extent variable from almost entirely across the chamber in some specimens to less than halfway in others; retral processes contain spines on their sides, extending to considerable depths into the canal region, but none on the top; low, rounded papillae common on the chamber surface; apertural face roughly triangular, slightly concave with numerous low, rounded papillae; aperture consists of a varying number of small rounded openings, both at the base of the apertural face, usually 3 in number, and as areal openings above the base, from 3 to 10; apertural openings have a complete raised rim, which may be accompanied by low papillae on the sides; wall calcareous, radial, finely perforate.

REMARKS.—*Elphidium crespinae* Cushman, known from middle Oligocene to middle Miocene strata in Australia, differs from *E. neocrespinae* in having more chambers in the last whorl (16 to 18), narrower chambers, more strongly biconvex shape with a more acute periphery and a stronger keel, in having a depressed umbilicus in most specimens, and commonly a more lobulate periphery. The morphologic variation of most characters within a population sample of *E. crespinae* is considerably greater than in samples of *E. neocrespinae*. The wide range of morphology in *E. crespinae* places the extreme specimens of that species very close to those of *E. neocrespinae*.

*Elphidium subplanatum* Cushman, described from the upper Oligocene to lower Miocene of Germany, differs in having more chambers, about 20 to 22 in the final whorl, and a wider area of more conspicuous bosses in the umbilical region. The probable continuation of the lineage in the Australasian area is through *E. crassatum* Cushman, described from middle Miocene to middle Pliocene strata in Australia, which differs in having more chambers in the last whorl, about 20, a slightly depressed umbilicus containing a low umbo, and a more biconvex test with a more acute periphery. Species morphologically similar to *E. neocrespinae* are found among later Cenozoic faunas in widely distributed areas. Species described include: *E. novo-zealandicum* Cushman, known from late Miocene to Holocene faunas in New Zealand and a likely continuum of the lineage in the Australasian area, which differs from *E. neocrespinae* in having 20 or more chambers in the final whorl and a more biconvex test with a depressed umbilical region containing reticulate ornamentation; *E. jenseni* (Cushman), from living assemblages in Samoa and from Pliocene and Pleistocene strata of Japan (Asano, 1938) which differs in having more chambers and a more acute and keeled periphery; *E. pustulosum* Cushman and McCullock, from the Holocene of the west coast of North and South America, which differs in having more inflated later chambers, a stronger and sharper keel, and less well-developed retral processes; and *E. earlandi* Cushman, from the Atlantic Ocean off the coast of Spain, which differs in having fewer chambers and much less-developed retral processes.

The entire group of species of *Elphidium* with strong retral process development, including the above discussed species and numerous others in the *E. macellum–E. crispum* complex, have a wide geographic and stratigraphic distribution. Although Cushman (1939) states that the Eocene species of *Elphidium* have poorly developed retral processes, subsequent descriptions have shown specimens in the Pacific area from Eocene strata with well-developed retral processes. This group possibly originates with *E. hampdenense* Finlay, from the upper lower Eocene of New Zealand,

and continues in geographic range through slightly younger *E. aguafrescaense* Todd and Kniker and *E. skyringense* Todd and Kniker, from the middle Eocene of Chile. The above three species are strongly biconvex; among the first species with a compressed test are the middle to late Oligocene forms, including *E. crespinae* from Australia and *E. subplanatum* from Germany, indicating a spread into Europe. The development of species with strong retral processes continued, but the geographic extent, as in the earlier species, is mainly in the Pacific region, including the west coast of North America and through the Mediterranean area into the Atlantic coast of Europe or Africa. The species of *Elphidium* in Eocene and Oligocene strata in the Atlantic Coast of the United States generally have poorly developed retral processes, and the *E. macellum–E. crispum* complex does not make an appearance in this area, even in the Holocene, except for a distant relative, *E. advenum* (Cushman) [or *E. fimbriatulum* (Cushman)], which is found in Pliocene and younger strata and *E. neocrespinae*. The ancestral form of *E. neocrespinae* does not occur in the Atlantic Coast area of North America as far as can be determined from the earlier species of *Elphidium*. Although *E. neocrespinae* is found during an interval in the late Pliocene to early Pleistocene, it is absent from the later Pleistocene and Holocene deposits of the Atlantic Coast. This relatively short time range for the species makes it useful for correlation.

*Faujasina compressa* Margerel (1971) is similar in many morphologic features to *E. neocrespinae*, such as canal system and sutural arrangement, apertural characteristics, and general surface ornamentation, but differs in being slightly planoconvex with a spiral side. The group of three species of *Faujasina* discussed by Margerel appears in the Pliocene and Pleistocene deposits of northern Europe, close in time to the appearance of *E. neocrespinae* in the eastern United States.

Occurrence.—Moderately rare throughout the area, composing up to 2 percent of the foraminiferal assemblages, but it is found in most samples and, with its relatively large size, is a conspicuous member of the fauna. Specimens are found in the following units: the Croatan Formation at the Lee Creek Mine, North Carolina; the Waccamaw Formation in southern North Carolina at Walkers Bluff and Neils Eddy Landing on the Cape Fear River, an outcrop 1 mile (1.6 km) east of Neils Eddy Landing, a marl pit at Acme, marl pits at Old Dock, and the Pierce Brothers Quarry 8 miles (12.8 km) southwest of Wilmington; the Waccamaw Formation in South Carolina at Tillys Lake; the James City Formation of DuBar and Solliday (1963) at James City, North Carolina; and the uppermost part of the "Yorktown" Formation along the Chowan River, North Carolina at Colerain Landing, Mt. Gould Landing, one-half mile (0.8 km) south of Mt. Gould Landing, and Black Rock Landing.

Stratigraphic Range.—Based upon the ranges of the co-occurring planktonic Foraminifera, E. *neocrespinae* has a probable range of zones N21 (upper Pliocene) and N22 (lower Pleistocene). *Elphidium neocrespinae* is absent from the many samples examined from the Duplin Formation in North and South Carolina and the Yorktown Formation in North Carolina and Virginia, most of which are dated as belonging to zones N19/N20 and probably lower N21. The species is also absent from the upper Pleistocene strata in North Carolina, such as exposed at Flanners Beach and Terra Ceia, from upper Pleistocene deposits in Virginia and Maryland (Langleys Bluff and Cornfield Harbor), and from the living faunas off the coast.

Type-Locality.—The locality for the holotype and figured paratypes is the Lee Creek Mine, North Carolina, in the Croatan Formation. Unfigured paratypes are from the Waccamaw Formation at Old Dock and Walkers Bluff, North Carolina, and from the "Yorktown" Formation one-half mile (0.8 km) below Mt. Gould Landing on the Chowan River, North Carolina.

Types.—The holotype is USNM 240133; figured paratypes are USNM 240130, USNM 240131, and USNM 240132; all of which are from USGS locality 25997. Unfigured paratypes are USNM 240148 from USGS locality 26021,

USNM 240149 from USGS locality 25926, and USNM 240150 from USGS locality 25927.

### *Elphidium compressulum* Copeland

PLATE 19: FIGURES 5, 6; PLATE 21: FIGURES 14, 15

*Elphidium compressulum* Copeland, 1964:262–263, pl. 37: figs. 3a,b.

DESCRIPTION.—Test planispiral, involute, strongly compressed; outline an elongate oval, not lobulate in early portion but may be slightly to moderately so in later portions; periphery narrowly rounded; umbilical region may be slightly depressed, commonly containing one small boss or may be completely filled with clear shell material flush with chamber walls; chambers compressed in early portion of final whorl, later becoming slightly inflated; 9 to 12 chambers in last whorl; sutures distinct, slightly depressed to flush with surface, may be thickened, slightly to moderately recurved; short retral processes well developed; aperture composed of small rounded openings at base of apertural face as well as areal openings; wall moderately coarsely perforate.

DISCUSSION.—The extreme compression of the test, the presence of short and broad, but well-defined retral processes, thickened sutures below the retral processes, and coarse wall porosity characterize this species. Some specimens from the Waccamaw and Croatan formations are less compressed and have an umbilical umbo projecting above the chamber surface.

OCCURRENCE.—The initial description of this species was from the Duplin Formation in southern North Carolina, and is most widely found there, in abundances up to 3 percent. It is fairly widespread in abundances of less than 1 percent in the Waccamaw and Croatan formations in central and southern North Carolina. The species occurs at some localities in the upper part of the Yorktown Formation, particularly those near Suffolk in southeastern Virginia.

STRATIGRAPHIC RANGE.—The known range of this species is from the upper part of the Yorktown and Duplin formations (probably middle Pliocene) to the lower Pleistocene strata of the Croatan and Waccamaw formations.

### *Elphidium gunteri* Cole

PLATE 19: FIGURES 7, 10

*Elphidium gunteri* Cole, 1931:34, pl. 4: figs. 9, 10.—Cushman, 1939:49, pl. 13: fig. 10.—Copeland, 1964:263, pl. 37: fig. 4a,b.

DESCRIPTION.—Test free, planispiral, involute, slightly compressed; periphery broadly rounded, not lobulate; umbilical regions usually filled with a series of large pustules, as many as 15, occasionally containing only a single large boss or entirely lacking any filling; chambers distinct, 12 to 15 in last whorl; sutures usually radial, sometimes slightly recurved, well marked by retral processes; retral processes well developed along entire sutural area, may be raised above chamber surface; wall rather coarsely perforate; aperture composed of rounded openings at base of apertural face.

DISCUSSION.—Test shape, type of umbilical filling, and development of the retral processes vary in *E. gunteri*. The test varies from a very broad oval shape with almost parallel sides and a broadly rounded periphery to a more compressed shape that tapers from the umbilical region toward the more narrowly rounded periphery. The most common type of umbilical filling is a series of about 10 moderate-sized clear pustules; however, in some specimens there may be several pustules or just one large pustule or boss, or in smaller specimens nothing in the umbilical area. The retral processes vary in development; they may be very strong and extend across much of the chamber and have a rounded shape that is raised above the chamber surface or be considerably shorter and have a flattened shape that is flush with the chamber surface.

OCCURRENCE.—This species is commonly found in low frequencies, up to 3 percent, in most of the samples from the Croatan Formation in the Lee Creek Mine, the Duplin and Waccamaw formations in southern North Carolina, and the uppermost part of the "Yorktown" Formation in the

beds along the Chowan River in northeastern North Carolina.

STRATIGRAPHIC RANGE.—In addition to its range from the middle Pliocene (Duplin) to the lower Pleistocene (Croatan, Waccamaw) in North Carolina, the species is known from the Caloosahatchee Formation (upper Pliocene and lower Pleistocene) in Florida and also is found living in the Gulf of Mexico. The range for the southeastern United States would be from middle Pliocene to Holocene.

### *Elphidium latispatium latispatium* Poag, new status

PLATE 22: FIGURES 3, 11, 12, 15, 16

*Elphidium latispatium* Poag, 1966:415, pl. 7: figs. 3, 4.
*Elphidium* cf. *E. poeyanum* (d'Orbigny).—Cushman and McGlamery, 1938:106, pl. 25: figs. 5, 7.

DESCRIPTION.—Test planispiral, involute, moderately compressed; periphery broadly rounded, slightly lobulate; umbilical regions flush to slightly depressed, commonly containing 3 or 4 irregular bosses; chambers distinct, increasing slowly in size, 10 to 12 in last whorl; sutures incised, slightly recurved; retral processes well developed along most of suture except for periphery; processes relatively short, may have slight inflation at proximal end giving bulbous appearance; aperture composed of small, rounded openings at base of apertural face; wall calcareous, finely perforate.

REMARKS.—A comparison was made between Cushman and McGlamery's specimens and other specimens from the Chickasawhay Formation at Choctaw Bluff and a topotypic population sample of *E. latispatium latispatium*, described from the overlying Paynes Hammock Formation. There is a close similarity in most characteristics, except that the specimens from the Chickasawhay at Choctaw Bluff generally have slightly shorter retral processes and a more bulbous shape (Plate 22: figures 11, 12, 15). This subspecies has shorter retral processes than those found in *E. latispatium pontium*.

OCCURRENCE.—Poag (1966) recorded this form from the Chickasawhay Formation in Mississippi, the Paynes Hammock Formation in Alabama and Mississippi, and the Tampa Limestone in Florida. The subspecies is also found in Cushman and McGlamery's material from the Chickasawhay Formation in Alabama. Examination of the Smithsonian collections yielded specimens identified as *Elphidium* species from the Frio Clay in Texas, which also belong to this taxon. The specimens are from a depth of 5805 to 5810 feet (1769 to 1770.8 m), described as 600 feet (182.8 m) below the top of the Frio in Magnolia Petroleum Company's Corpus Christi Bank #2, Plymouth Field, San Patricio County, Texas. A note on the back of the slide states that this form is found throughout the Frio. This form has not been recognized in the Atlantic Coast.

STRATIGRAPHIC RANGE.—This subspecies ranges through the Chickasawhay and Paynes Hammock formations, which were dated by Poag (1972a:266) as late Oligocene in age, equivalent to zones N2–N3.

### *Elphidium latispatium pontium*, new subspecies

PLATE 12: FIGURES 15, 16; PLATE 13: FIGURES 8, 9; Plate 19: FIGURES 8, 9; PLATE 22: FIGURES 9, 10, 13, 14

*Elphidium poeyanum* d'Orbigny.—Dorsey, 1948:302, pl. 35: figs. 7a, 8b.

DESCRIPTION.—Test planispiral, involute, slightly to moderately compressed; periphery broadly rounded, slightly lobulate; umbilical regions flush to slightly depressed, commonly contain 3 or 4 irregular bosses; chambers distinct, increasing slowly in size, 10 to 12 in last whorl; sutures incised, usually radial to slightly recurved in later chambers, slightly to moderately recurved in earlier; retral processes well developed along entire sutural area, bridges vary in width from moderately thin to broad; aperture composed of small, rounded openings at base of apertural face; wall finely perforate, calcareous, optically radial.

REMARKS.—This species is the oldest *Elphidium*

in the Oligocene and Miocene of the central Atlantic region, and is followed by a number of species in the uppermost Miocene and Pliocene of Virginia and North Carolina.

This subspecies differs from *E. latispatium latispatium* by having longer retral processes that continue across the periphery, and by the later sutures being less recurved to radial. The population from the Silverdale beds of Vokes (1969), although belonging to *E. latispatium pontium*, has individuals with short retral processes approaching those found in *E. latispatium latispatium.*

Dorsey (1948) and Cushman and McGlamery (1938) incorrectly placed this subspecies in *E. poeyanum. Elphidium poeyanum* differs in having fewer chambers (7 to 9) in the last whorl, a more coarsely perforate wall, a more depressed umbilicus, a more elongate test outline, and more recurved sutures in the later part of the test.

Several species described from the Oligocene and Miocene of Europe have characters similar to this species. They include *Elphidium antoninum* (d'Orbigny), *E. listerii* (d'Orbigny), *E. hauerinum* (d'Orbigny), *E. rugosum* (d'Orbigny), *E. minutum* (Reuss), *E. latidorsatum* (Reuss), and *E. articulatum* (d'Orbigny). These species all differ from *E. latispatium* in variable combinations of characters, but do belong in a closely related grouping. Twelve specimens on a slide in the Smithsonian USNM collections, labeled only "*E. rugosum* d'Orbigny, Sarmat," do not belong to that species but do belong to *E. latispatium pontium*, confirming the European connection of this group.

*Elphidium gunteri* Cole differs in having longer and stronger retral processes, a more inflated test shape, and generally more umbilical bosses.

*Elphidium excavatum* (Terquem) includes 5 subspecies (Feyling-Hanssen, 1972). In addition to the nominate form, they are *E. excavatum clavatum* Cushman, *E. excavatum selseyensis* (Heron-Allen and Earland), *E. excavatum alba* Feyling-Hanssen, and *E. excavatum lidoensis* Cushman. Although these taxa show considerable variation among themselves, they differ as a group from *E. latispatium* by having poorly developed retral processes, fewer chambers, papillae in umbilical, apertural, and sutural areas, more convexity of test in umbilical regions, and generally either a large boss or many small bosses in the umbilicus.

Occurrence.—This subspecies occurs in the Silverdale beds of Vokes (1967) in Jones, Carteret, Craven, and parts of adjacent counties in the central part of eastern North Carolina, and in the lower and middle parts of the St. Marys Formation in Calvert and St. Marys counties, Maryland.

Stratigraphic Range.—The range of this subspecies is from the upper Oligocene and lower Miocene (zones N3–N4), to probable middle Miocene (post-zone N11).

Type-Locality.—The type locality for the holotype and some of the figured and unfigured paratypes is Langley's Bluff on the western shore of Chesapeake Bay, St. Marys County, Maryland, in the St. Marys Formation. The other figured and unfigured paratypes are from the Silverdale beds of Vokes (1967) southeast of Maysville, Jones County, North Carolina, on the Long Point Road to the White Oak River.

Types.—The holotype is USNM 252571 from USGS locality 25955; figured paratypes are USNM 252572 and 252573 from USGS locality 25955, and USNM 252574 and 252575 from USGS locality 22294. Unfigured paratypes are USNM 252576 from USGS locality 25955, and USNM 252577 from USGS locality 22294.

### *Elphidium limatulum* Copeland

Plate 11: figures 9–12

*Elphidium limatulum* Copeland, 1964:263–264, pl. 37: fig. 5a–b.

Description.—Test free, planispiral, involute, moderately compressed; periphery broadly rounded; umbilical regions slightly to moderately depressed, containing 20 to 40 pustules of varying sizes; chambers increasing gradually in size, numbering 9 to 11 in last whorl; sutures deeply incised, moderately recurved; retral process development varies from the presence of 4 to 6 short, broad processes in the later chambers of larger speci-

mens to the total absence in medium to small specimens; aperture composed of small, rounded openings at the base of the apertural face; wall glossy, finely perforate.

Remarks.—The development of the retral processes is variable in this species. Large adult specimens usually have short, broad retral processes, particularly near the umbilicus in the later chambers (Plate 11: figure 11), but many medium- to small-sized individuals lack them completely (Plate 11: figure 9). The glossy wall, large number of umbilical pustules, and weak development of retral processes characterize the species.

Occurrence.—Rare to common throughout the Croatan Formation in the Lee Creek Mine, the Waccamaw and Duplin formations in southern North Carolina, and in the uppermost part of the "Yorktown" Formation as exposed along the Chowan River in North Carolina.

Stratigraphic Range.—The known range of this species is from the Duplin Formation (probably middle to upper Pliocene) to the lower Pleistocene (Croatan and Waccamaw formations).

## Genus *Cibicides* Montfort, 1808

Remarks.—During studies of the species of *Cibicides* on the scanning electron microscope, the presence of structures in the large pores was noted, first in *C. pungoensis*, new species, and subsequently in the other species as they were examined. The structures in the pores are sievelike in appearance. The pore pattern in the sieve plate is generally consistent within each of the species, although it differs among the species. The sieve plates are most readily visible on the umbilical side, particularly on the last several chambers. They are less prominent on the spiral side, also occurring most noticeably in the last several chambers, probably because the sieve plates are near the surface in the last two or three chambers, but are more deeply recessed in the earlier chambers in the whorl.

The arrangement of the pores in the sieve plates differs among species. In *C. pungoensis*, new species, the pores are small and numerous, as many as 20 to 25, mostly round with some elongate, and some of the interpore areas are considerably raised (Plate 13: figures 3, 10). In *C. cravenensis*, new species, the pores are large and few in number, from 1 to 4, mostly irregular in shape, and have a raised collar around the outside of the wall pore (Plate 14: figures 5, 7, 9). In *C. croatanensis*, new species, the sieve pore pattern is more variable, particularly between the spiral and umbilical sides. Some specimens have 8 to 10 medium-sized rounded sieve pores with raised ridges between (most commonly on the umbilical side), and others have a thin, flat plate with several irregular openings (most commonly on the spiral side) (Plate 10: figures 8, 10).

Several descriptions of structures within the pores of Foraminifera have been made, including the "foraminal plugs" in *Elphidium crispum* (Jepps, 1942:625–627), "bouchons" in *Planorbulina mediterranensis* (Le Calvez, 1938:236, 1947), "dark disks" in *Discorbis erecta* (Le Calvez, 1947), "sieve plates" in several species (Jahn, 1953), "pore plugs" in *Discorbinopsis aguayo* (Arnold, 1954a, 1954b), and "sieve plates" in *Amphistegina* (Hansen, 1972b). The reported pore structures vary in position and shape, and include structures with similarity to the presently figured ones; however, all the previously described pore structures are of organic composition and thus differ from the present ones, which are largely calcareous.

It is not known at present whether calcareous "sieve plates" are widespread in species of *Cibicides* or restricted to this group of species from the Oligocene through lower Pleistocene in the Atlantic Coastal Plain.

### *Cibicides cravenensis*, new species

Plate 14

Description.—Test trochospiral, biconvex, spiral side slightly to moderately convex, umbilical side moderately to strongly convex; broad, prominent umbo on umbilical side; periphery very slightly lobulate, keeled, acute; chambers compressed, increasing gradually in size, 11 to 13 in

last whorl; sutures strongly recurved on both sides, moderately limbate and raised on both sides; aperture a narrow slit along inner margin of spiral side of final chamber and extending as an arch onto umbilical side, with thickened rim; wall calcareous, optically indistinctly radial, coarsely perforate on both sides, pores on both sides commonly containing "sieve plates" with 1 to 5 irregular openings, pores commonly surrounded by raised collar.

REMARKS.—The distinguishing characters of this species are the broad umbo on the spiral side, convex umbilical side, limbate, raised, curved sutures on the umbilical and spiral sides, keel throughout, and coarse pores on both sides.

*Cibicides cravenensis*, new species, and *C. pungoensis*, new species, differ by the latter having a strongly lobulate and irregular adult form with nonlimbate, depressed sutures on the umbilical side and a flat spiral side that has more strongly limbate and raised sutures. *Cibicides elomoensis* Rau differs in being smaller in size and having a less conspicuous keel. *Cibicides cravenensis* is distinguished from *C. falconensis* Renz by having a stronger umbo and more limbate sutures on the umbilical side and a more convex spiral side. *Cibicides cravenensis* is similar to *C. floridanus* (Cushman), but has a stronger keel, broader and more highly raised sutures on both sides, and is more coarsely perforate on the umbilical side.

OCCURRENCE.—This species is abundant in the subsurface in the limey facies of the Pungo River Formation in the Croatan National Forest area between New Bern and Morehead City, North Carolina.

STRATIGRAPHIC RANGE.—The range is upper lower Miocene (zone N8), with a possibility of a slightly lower limit in the lower Miocene.

TYPE-LOCALITY.—The holotype and figured and unfigured paratypes are from a well core at a depth of 48.5 to 49.5 feet (14.7 to 15.0 m) near Great Lake in Craven County, North Carolina.

TYPES.—The holotype is USNM 252527, figured paratypes are USNM 252528 through 252532, 10 unfigured paratypes are USNM 252533; all of which are from USGS locality 26018.

### *Cibicides croatanensis*, new species

PLATE 10: FIGURES 5–8, 10; PLATE 20: FIGURES 5–9

DESCRIPTION.—Test trochospiral, plano-convex with umbilical side moderately convex, spiral side commonly has undulating surface consisting of depressions at sutures and strong overgrowths on early chambers; small umbo on umbilical side, more pronounced in early stages; periphery slightly to moderately lobulate, subacute, slight keel throughout; chambers compressed, increasing gradually in size, 9 to 10 in last whorl, later chambers sometimes irregular in shape; sutures strongly recurved on spiral side, less recurved on umbilical side; moderately limbate on both sides in early stages, becoming slightly limbate and depressed in later stages; aperture a narrow slit along inner margin of spiral side of final chamber and extending as a broad arch with thickened rim onto umbilical side; wall calcareous, optically indistinctly radial, coarsely perforate on both sides, pores deeply set in wall with thickened ridges between pores, thickening of wall in earlier chambers of last whorl covers many of the pores and is more prevalent on umbilical side, pores on both sides commonly containing sieve plates; on umbilical side, most sieve plates have as many as 10 rounded openings with raised ridges inbetween, on spiral side plates have as many as 5 irregular openings in a generally flat plate.

REMARKS.—This species is characterized by having coarse pores, deeply set in thickened wall on both sides, a flat spiral side with thickened surface over early chambers, and a moderately convex umbilical side with recurved limbate sutures.

*Cibicides croatanensis* differs from *C. altamiraensis* Kleinpell in having coarser pores and more strongly limbate and raised sutures on the umbilical side. *Cibicides croatanensis* is distinguished from *C. ornatus* (Cushman) by having fewer chambers in the last whorl, coarser pores, and lacking pustules on inner chambers on the spiral side.

OCCURRENCE.—Rare to common (as much as 4.5 percent) in the Croatan Formation in the Lee Creek Mine. It also occurs in abundances of less than 1 percent in scattered localities in the Wac-

camaw Formation in southern North Carolina, including Acme and Old Dock, and in the uppermost beds of the "Yorktown" Formation along the Chowan River in northeastern North Carolina at Mt. Gould Landing and Black Rock Landing.

STRATIGRAPHIC RANGE.—Upper Pliocene to lower Pleistocene (zones N21–N22).

TYPE-LOCALITY.—The holotype and figured and unfigured paratypes are from the Lee Creek Mine, North Carolina, in the Croatan Formation.

TYPES.—The holotype is USNM 252534, figured paratypes are USNM 252535 to 252539, 10 unfigured paratypes are USNM 252540; all of which are from USGS locality 25997.

### *Cibicides pungoensis*, new species

PLATE 13: FIGURES 1–7, 10

DESCRIPTION.—Test medium to large, trochospiral, spiral side flat to strongly concave, umbilical side slightly to strongly convex, becoming partially evolute in later chambers; strongly projecting umbo on umbilical side; in early stages periphery subrounded, slightly lobulate with keel, becoming strongly lobulate and acute with less-developed keel in later stages; chambers increasing gradually in size, 9 to 11 in last whorl, later chambers irregular in shape; sutures strongly recurved on spiral and umbilical sides, limbate and raised in early stages on umbilical side, gradually becoming nonlimbate and moderately depressed in later stages on both sides; aperture a narrow slit along inner margin of spiral side of final chamber and extending as an arch onto umbilical side, with thickened rim; wall calcareous, optically indistinctly radial, coarsely perforate on both sides, pores on both sides containing sieve plates that have small circular to oval pores, as many as 25, and raised ridges between pores.

REMARKS.—This species is characterized by the prominent umbo, strongly limbate and raised sutures in the early stages, which become nonlimbate and depressed in the later stages on the umbilical side; a circular and slightly lobulate early shape, which becomes highly lobulate and somewhat evolute in the later stages, and coarse pores on both sides. The test may have a strongly concave spiral side, a shape attributed in *C. lobatulus* (Walker and Jacob) to attachment to seaweed during growth.

The change in outline during growth from circular to irregular and strongly lobulate also is similar to that found in *C. lobatulus* by Nyholm (1961). *Cibicides pungoensis* differs in having a strongly developed umbo and limbate sutures, and generally is more coarsely perforate, especially on the umbilical side. *Cibicides pungoensis* differs from *C. cravenenisis* in its more lobulate adult shape and a flat to concave spiral side with less limbate and raised sutures.

OCCURRENCE.—Rare to common in the "Virginia St. Marys" beds in the Gatesville Well, North Carolina, at depths of 131 to 138 feet (39.9 to 42.0 m).

STRATIGRAPHIC RANGE.—Upper Miocene.

TYPE-LOCALITY.—The holotype and figured and unfigured paratypes are from the Gatesville Well, North Carolina, at a depth of 131.5–132 feet (40.0 to 40.2 m) in the "Virginia St. Marys" beds.

TYPES.—The holotype is USNM 252541, figured paratypes are USNM 252542 to 252544, 10 unfigured paratypes are USNM 252545; all of which are from USGS locality 25992.

## Genus *Virgulinella* Cushman, 1932

### *Virgulinella miocenica* (Cushman and Ponton), new combination

PLATE 10: FIGURE 3; PLATE 17: FIGURES 12, 17, 18

*Virgulina miocenica* Cushman and Ponton, 1931:32, pl. 4: figs. 14–16.

*Virgulina* (*Virgulinella*) *miocenica* Cushman and Ponton.—Cushman, 1937:35, pl. 5: figs. 15–16.—Dorsey, 1948:305, pl. 36: fig. 12.

DESCRIPTION.—Test elongate, about 3 times as long as wide, tapering toward both ends; early part of test may be straight or curved; chambers inflated, distinct, with numerous arcuate projec-

tions to previous chambers; sutures distinct, with arcuate pattern; aperture elongate, narrow, straight to slightly curved, extending from base of final chamber nearly to apex, with toothplate; wall smooth, glassy, finely perforate.

OCCURRENCE.—Rare to common throughout the Calvert, Choptank, and St. Marys formations in Maryland and northern Virginia, the Pungo River Formation in North Carolina, and through the "Virginia St. Marys" in Virginia.

STRATIGRAPHIC RANGE.—The range in the central Atlantic Coastal Plain is from uppermost lower Miocene (zone N8) to the top of the upper Miocene (probably near the end of zone N17).

## Genus *Astrononion* Cushman and Edwards, 1937

### *Astrononion stelligerum* (d'Orbigny)

PLATE 11: FIGURES 13–16; PLATE 12: FIGURES 1, 2

*Nonionina stelligera* d'Orbigny, 1839:128, pl. 3: figs. 1, 2.
*Astrononion stelligerum* (d'Orbigny).—Cushman and Edwards, 1937:31, pl. 3: fig. 7a,b.—Hornibrook, 1964:334, pl. 1: figs. 5–9, 14, 15.—Le Calvez, 1974:37–38, pl. 9: figs. 1–4.

DESCRIPTION.—Test free, relatively small, planispiral, involute, moderately to strongly compressed; periphery rounded, umbilical regions slightly depressed; chambers increasing gradually in size, 7 to 9 in last whorl; sutures distinctly incised, slightly recurved; in early part of last whorl relatively narrow tubes are present along sutures, extending from umbilicus about one-third of way along the sutures with outer ends of tubes opening into sutures; in later part of last whorl tubes are modified into flattened essentially triangular plates that are attached to chamber on anterior side and open down outermost part of posterior side; plates join in umbilical region forming large plate over area; aperture is low, simple, rimmed, arched slit at base of final chamber.

REMARKS.—A neotype for this species has been selected by both Hornibrook (1964) and Le Calvez (1974). Each noted that the type specimen had "disintegrated." Topotypic material from Teneriffe Island was not available to Hornibrook, so he picked a specimen from the nearby island of Las Palmas as the neotype. As all the conditions for the establishment of a neotype appear to have been met by Hornibrook, his designation of the neotype would stand even though Le Calvez subsequently designated a specimen from the d'Orbigny collection from Teneriffe as neotype. A comparison of the illustrations of each neotype shows that both appear to be well within the variation of the species.

The specimens in the present material generally have fewer chambers, ranging from 7 to 9 in comparison to 10, and a more pronounced umbilicus than those illustrated by Hornibrook and Le Calvez.

OCCURRENCE.—Except for one specimen found in the lower Pliocene part of the Yorktown Formation in Virginia, this species is rare in the Croatan Formation in North Carolina (upper Pliocene and lower Pleistocene).

STRATIGRAPHIC RANGE.—Although found in the Pliocene and Pleistocene of the Atlantic Coastal Plain, this species has been recorded from lower Miocene strata in Europe and New Zealand, and continues into the modern fauna.

## Genus *Florilus* Montfort, 1808

### *Florilus chesapeakensis*, new species

PLATE 11: FIGURES 7, 8; PLATE 18: FIGURES 7, 8, 11, 12

*Nonion medio-costatum* sensu Dorsey, 1948:300, pl. 35: fig. 4a–c.

DESCRIPTION.—Test relatively large, planispiral to slightly asymmetrical, longer than broad, with width increasing rapidly in later stages, periphery subrounded to subacute, umbilical regions slightly to moderately depressed, containing slight to moderate amount of pustulose material, which may extend onto apertural face; chambers distinct, about 13 in last whorl, much higher than wide, increasing abruptly in width as seen in apertural face, marked by slightly to sharply raised areas between sutures, raised areas extend

from the umbilicus to about halfway to the periphery; sutures distinct, slightly depressed, moderately to strongly limbate, especially in earlier chambers in last whorl, moderately recurved, containing single row of pustules extending as far as halfway to periphery; apertural face broadly heart-shaped, aperture a low, curved slit at base of apertural face; wall calcareous, finely perforate.

Remarks.—This species is characterized by the slightly to sharply raised areas between the inner parts of the sutures, the limbate sutures, and the abrupt increase in width of the heart-shaped apertural face. It differs from *Florilus medio-costatum* (Cushman) by having generally stronger raised areas between the sutures with the raised areas being found earlier in the last whorl, by more strongly limbate sutures, and in having a much more flaring test in the later chambers with the apertural face almost twice as wide. *Florilus costiferus* (Cushman) differs in having more chambers in the last whorl (approximately 20), lacking the raised chamber areas, and having more strongly limbate sutures. *Florilus incisa* (Cushman) is similar except for the absence of the raised areas between the sutures.

Occurrence.—Rare to common in samples from the Calvert, Choptank, and St. Marys formations in Maryland and Virginia, and the Pungo River Formation in North Carolina.

Stratigraphic Range.—This species first occurs in beds placed in the uppermost lower Miocene (zone N8) and continues into upper Miocene strata.

Type-Locality.—The holotype is from Windmill Point on the St. Marys River, Maryland, in the St. Marys Formation. Figured paratypes are from the Calvert Formation at Governors Run, Maryland, and figured and unfigured paratypes are from the "Virginia St. Marys" beds in the Gatesville Well in North Carolina. Unfigured paratypes are from the Choptank Formation at Flag Pond, Maryland.

Types.—The holotype is USNM 252565 from USGS locality 25992; figured paratypes are USNM 252566 from USGS locality 25983, and USNM 252567 from USGS locality 25969; unfigured paratypes are 5 specimens, USNM 252568 from USGS locality 25992 and 5 specimens, USNM 252569 from USGS locality 25962.

## Genus *Nonion* Montfort, 1808

### *Nonion advenum pustulosum*, new subspecies

Plate 22: figures 1, 2, 4–6

Description.—Test planispiral, circular to oval in side view, moderately compressed; periphery broadly rounded, slightly lobulate; umbilical region not depressed, filled with a small to occasionally moderate-sized boss and moderate to large amount of small pustules, with pustules extending onto excavated sutures and apertural face; 10 to 13 chambers in last whorl; sutures deeply incised on chamber sides, slightly so on periphery, with deep excavation near boss, moderately recurved; aperture composed of small, rounded openings at the base of the apertural face; wall calcareous, optically granular, finely perforate.

Discussion.—This subspecies is characterized by a generally small umbilical boss, abundant pustulose material, excavated sutures, and 10 to 13 chambers in the last whorl.

Populations of *Nonion advenum advenum* (Cushman) differ in generally having a larger umbilical boss, a more discoid shape with a subacute periphery, more extensive excavated sutures, and less pustulose material. A specimen from the Chickasawhay Formation at Choctaw Bluff on the Alabama River is illustrated (Plate 22: figures 7, 8). Some specimens of *N. advenum pustulosum* in the populations from North Carolina have a larger umbilical boss and less pustulose material and approach the minimum development of those characters in specimens of *N. advenum advenum* from Alabama.

*Nonion advenum pustulosum* is larger than *N. calvertensis*, new species, and has more chambers in the last whorl, a smaller boss, and more pustulose material.

*Nonion inexcavatum* (Cushman and Applin) dif-

fers in having a more compressed test with a subacute periphery, a larger umbilical boss, and the absence of excavated sutures in the umbilical area.

Occurrence.—This subspecies occurs in the "Silverdale-age" beds on the central Atlantic Coastal Plain area of North Carolina, particularly exposures in Onslow, Craven, and Carteret counties. The subspecies is usually abundant, composing more than 50 percent of the total assemblage in some samples.

Stratigraphic Range.—The subspecies is restricted to the upper Oligocene Silverdale beds of Vokes (1967) (probably zones N2–N3). It is not found in the overlying uppermost lower Miocene Pungo River Formation (zones N8–N10).

Type-Locality.—The type-locality for the holotype, figured paratypes, and unfigured paratypes is near Long Point on the White Oak River, Carteret County, North Carolina.

Types.—The holotype is USNM 252561, figured paratypes are USNM 252562 and 252563, and 10 unfigured paratypes are USNM 252564, all of which are from USGS locality 22294.

### *Nonion calvertensis*, new species

Plate 12: figures 3–8; Plate 19: figures 1, 2

*Nonion advenum* sensu Dorsey, 1948:299–300, pl. 35: fig. 1a–c.

Description.—Test planispiral, small, nearly circular in side view, moderately compressed; periphery broadly rounded; umbilical region filled with a large clear boss that may be even in height with sides of chambers or project well beyond them; the boss is joined to the chamber sides in the earlier chambers of the last whorl, but not in the last 3 or 4 chambers; a small amount of pustulose material is found in the umbilicus, extending up the sutures and onto the apertural face; chambers increasing gradually in size, numbering 8 to 10 in the last whorl; sutures deeply incised on chamber sides, not on periphery, with deep excavation nearing boss, moderately recurved; aperture composed of small, rounded openings at the base of the apertural face; wall finely perforate, calcareous, optically granular.

Discussion.—This subspecies is characterized by its small size and circular shape with a rounded periphery, 8 to 10 chambers in the last whorl, a prominent umbilical boss in most specimens and having the inner part of the sutures excavated and containing a small amount of pustulose material. *Nonion advenum advenum* (Cushman), found in Eocene and Oligocene strata in the southeastern United States, shows considerable variation both within and between populations, but generally differs by being larger, as much as twice as large, having more chambers in the last whorl, 10 to commonly 15, and by having a more discoid-shaped test with a subacute periphery.

*Nonion advenum pustulosum*, new subspecies, from the upper Oligocene of North Carolina differs by being larger in size, having more chambers in the last whorl, 10 to 13, by largely lacking a prominent boss, and by having a larger amount of pustulose material in the umbilical, sutural, and apertural areas.

Occurrence.—The distribution is limited to the lower and middle part of the Calvert Formation in Maryland, from beds 3 to 10 of Shattuck. The highest frequencies are found in the lower beds, reaching a peak of 14 percent in bed 8, and the lowest, less than 1 percent, in bed 10.

Stratigraphic Range.—Upper part of bed 3 (probably zone N8) through bed 10 (zone N9) of Calvert Formation.

Type-Locality.—The type-locality is Randle Cliffs on the western shore of Chesapeake Bay, Calvert County, Maryland, in bed 6 of the Calvert Formation.

Types.—The holotype is USNM 252554; figured paratypes are USNM 252555–252558; all of which are from USGS locality 25980 in bed 6. Unfigured paratypes are USNM 252559 from USGS locality 25980 in beds 5 and 6, and USNM 252560 from USGS locality 26022.

### *Nonion marylandicum* Dorsey

Plate 12: figures 9–14; Plate 18: figures 9, 10

*Nonion marylandicum* Dorsey, 1948:301, pl. 35: fig. 2a–c.

Description.—Test planispiral, involute, moderately compressed; periphery broadly rounded;

umbilical regions slightly depressed, filled with small pustules that also extend outward along the sutural areas; chambers may increase gradually in size in last whorl or in large specimens may have a relatively constant size; 7 to 9 chambers in last whorl; sutures deeply incised, moderately recurved; aperture a narrow slit at base of apertural face; wall finely perforate.

Remarks.—This species is variable in the size and shape of chambers in the last whorl, largely dependent upon the size of the individual. Smaller specimens have 7 relatively compressed chambers with increasing chamber size and a small to moderate amount of pustulose material (Plate 12: figures 11, 13). Large specimens have 8 or 9 more inflated and fairly equal-sized chambers in the last whorl, and a large amount of pustulose material in the umbilical area (Plate 12: figure 9).

Occurrence.—Rare throughout the upper part of the Calvert Formation in Maryland and the Choptank Formation in Maryland and Virginia. Dorsey (1948) also reported this species in the overlying St. Marys Formation in Maryland. None of her specimens from the St. Marys Formation could be found in the Smithsonian collections, but specimens collected by the author from the same localities include two species that could have been misidentified as *N. marylandicum.* One is a species of *Nonion*, represented by only a few specimens, which differs from *N. marylandicum* in having very few umbilical pustules. The other, represented by more specimens, is a species of *Anomalinoides*, characterized by a low trochospiral coiling and small amount of pustulose material in the umbilical region.

Stratigraphic Range.—The range is from bed 10 of the Calvert Formation upward through the Choptank Formation, which gives a middle Miocene age, ranging from uppermost zone N8 to lowermost N9 to later than zone N11.

## Genus *Svratkina* Pokorný, 1956

Remarks.—The only previously known occurrences of this genus in the New World are of *S. lajollaensis* Sliter from the Upper Cretaceous of southern California and the living *S. decorata* (Phleger and Parker) from the Gulf of Mexico.

Three new occurrences of this genus in North America were found: *S. croatanensis*, new species from the upper Pliocene part of the Croatan Formation of North Carolina and Virginia, an as yet undescribed species from upper Oligocene strata in North Carolina, and *S. crassicoria* (Poag) from the Paynes Hammock Formation (upper Oligocene) of Alabama and Mississippi.

The depth distribution of the living species within this genus is variable; *S. tuberculata* Balkwill and Wright is found in shelf waters and *S. decorata* is characteristic of depths from 1300 to 3550 m.

Four species were placed in *Svratkina* by Pokorný (1956). One of these, *Discorbina turris* Karrer, 1868, does not appear to belong to this genus based upon examination of a topotype specimen in the Smithsonian USNM collections and comparison with the original illustration. In *D. turris*, the suture pattern is radial on both sides and the aperture is round and umbilical in position, characteristics not consistent with the generic concept of *Svratkina. D. turris* probably belongs in *Glabratella* Dorreen, 1948.

### *Svratkina croatanensis*, new species

Plate 15

Description.—Test free, trochospiral, oval in outline; about 7 chambers in last whorl; all chambers visible on the spiral side, only those of the last formed whorl visible on the umbilical side; both left and right coiled specimens; sutures moderately curved on spiral side, radial to slightly curved on umbilical side; spiral side varies from essentially planar to moderately convex, umbilical side from slightly to moderately convex; periphery broadly rounded to subrounded; aperture a long narrow opening of variable height and distinctness, extending from near the umbilicus to near the periphery, without lip, but having funnel-like projection into previous chamber; wall calcareous, spiral side coarsely perforate, pores with thickened rims opening on top of low tubular necks; size of pores variable, long slits

common, probably as a result of connection of a series of pores; pores scattered over most of spiral surface except for early chambers, with linear concentrations sometimes found along sutures; umbilical side largely imperforate, but some large pores are occasionally found near the periphery.

REMARKS.—This species is distinguished by the large pores that commonly coalesce into slit-like openings on the spiral side, and few pores on the umbilical side. *Svratkina tuberculata* (Balkwill and Wright) is distinguished by having strongly elevated tubercles over much of the umbilical surface. *Svratkina australiensis* (Chapman, Parr, and Collins) differs in having more pores on the umbilical side; even, moderate-sized pores on the spiral side; a very convex spiral side; even, moderate-sized pores on the spiral side; a very convex spiral side; and more chambers (9) in the last whorl. *Svratkina decorata* (Phleger and Parker) differs in having few, scattered fine tubercles. *Svratkina perlata* (Andreae) is the most similar species, but has finer pores, which also cover much of the umbilical side. Also, a lesser degree of alignment of pores is seen along the sutural areas on the spiral side.

OCCURRENCE.—Abundances of less than 1 percent in the lower part of the Croatan Formation in the Lee Creek Mine and at depths between 112.5 and 113 feet (34 and 34.4 m) in the Norfolk, Virginia, Moores Bridge Well.

STRATIGRAPHIC RANGE.—The species is restricted to the Croatan Formation and uppermost part of the "Yorktown" Formation, indicating a late Pliocene and early Pleistocene age.

TYPE-LOCALITY.—The locality for the holotype and some of the figured paratypes is the Lee Creek Mine, in the lower part of the Croatan Formation. Additional figured paratypes are from the Norfolk, Virginia, Moores Bridge Well at a depth between 112.5 and 113 feet (34 and 34.4 m).

TYPES.—The holotype is USNM 252546 from USGS locality 25997; figured paratypes are USNM 252547 and 252548 from USGS locality 25997 and USNM 252549–252553 from USGS locality 26001.

## Register of USGS Localities

(Each locality is listed in the following order: number of locality, formation, location and description of collection site, collector, and date of collection.)

22294. Silverdale beds of Vokes (1967). Few inches (cm) of outcrop in bottom of gully south of Long Point Road about 0.5 miles (0.8 km) west of intersection with Haywood Landing Road; in Croatan National Forest, Jones County, North Carolina. P.M. Brown, Druid Wilson, and Alan Rubin, 17 November 1959.

25921. Chickasawhay Formation. Marl above hard limestone, Choctaw Bluff, Alabama River, Alabama (from Cushman Foraminifera Collection).

25922. Choctawhatchee Formation. Alice Creek, near N.E. corner of SE ¼ Sec. 8, T. 1N, R. 19W about 1 mile (1.6 km) NE of Old Parmenter Place, Walton County, Florida (from Cushman Foraminifera Collection).

25923. Duplin Formation. Natural Well, 2 miles (3.2 km) west of Magnolia, Duplin County, North Carolina. Four feet (122 cm) of bluish clayey sand exposed, sample 3 feet (91 cm) above base. T. Gibson, 1959.

25924. Duplin Formation. Marl pit on Barwick Farm southwest of Kenansville, Duplin County, North Carolina. Four feet (122 cm) of yellow clayey sand exposed, sample 3 feet (91 cm) above base. T. Gibson, 1959.

25925. Waccamaw Formation. Walker's Bluff on southern bank of Cape Fear River 9 miles (14.5 km) below Elizabethtown, Bladen County, North Carolina. Five feet (1.5 m) exposed; lowermost 2 feet (61 cm) of clayey sand with large pelecypods, upper 3 feet (91 cm) of yellow sand contains much shell hash: Sample 1 foot (30 cm) above base of section. T. Gibson, 1959.

25926. (same formation/location as 25925); sample 4 feet (122 cm) above base of section. T. Gibson, 1959.

25927. "Yorktown" Formation. Bluff at Mt. Gould on western bank of Chowan River in Bertie County, North Carolina. Five feet (1.5 m) of yellow clayey sand are exposed in upper part of bluff; sample 3 feet (91 cm) above base. T. Gibson, 1959.

25929. "Yorktown" Formation. Bluff on western side of Chowan River at Black Rock Landing in Bertie County, North Carolina, 1 mile (1.6 km) north of Highway 17 bridge. 9-foot (2.7-m) section exposed; sample 1½ feet (46 cm) above base of 3-foot (91-cm) unit of yellow fossiliferous sand that extends from 5 to 8 feet (1.5 to 2.4 m) above base of section. T. Gibson, 1959.

25930. (same formation/location as 25929); sample in middle of 2-foot (61-cm) bluish clayey sand unit that extends from 3 to 5 feet (0.9 to 1.5 m) above base of section. T. Gibson, 1959.

25933. Yorktown Formation. South bank of Yorktown River about 1 mile (1.6 km) downstream from Yorktown at base of Moore House bluff in James County, Virginia. 24 feet (7.3 m) of section exposed: sample 1 foot (30 cm) above base of 3-foot (91-cm)fossiliferous gray sand unit, which extends from 6 to 9 feet (1.8 to 2.7 m) above base of section, T. Gibson, 1959.

25934. (same formation/location as 25933); sample 2 feet (61 cm) above base of 4-foot (122-cm) brown sand unit, which extends from 2 to 6 feet (0.6 to 1.8 m) above base of section and contains few fossils. T. Gibson, 1959.

25937. Yorktown Formation. Bluff at Morgart's Beach on south bank of James River, 5 miles (8 km) north of Smithfield, Isle of Wight County, Virginia. 21.5 feet (6.6 m) of section exposed; sample 1.5 feet (46 cm) above base of 4-foot (122-cm) yellow sandy shell hash unit, which extends from 17.5 to 21.5 feet (5.3 to 6.6 m) above base of section. T. Gibson, 1959.

25941. Yorktown Formation. Bluff on western bank of Nansemond River 1½ miles (2.4 km) NE of Highway 258 bridge in the northern part of Suffolk, Nansemond County, Virginia. 13 feet (4 m) of yellow clayey sand exposed; lowermost 2 feet (61 cm) sparingly fossiliferous and upper 11 feet (3.4 m) very fossiliferous; sample 7 feet (2.1 m) above base of section. T. Gibson, 1959.

25942. (same formation/location as 25941): sample 8 feet (2.4 m) above base of section in *Mulinia congesta* bed. T. Gibson, 1959.

25948. Yorktown Formation. Maddry's Bluff on south bank of the Meherrin River 1 mile (1.6 km) downstream from Highway 258 bridge, 1 mile (1.6 km) northeast of Murfreesboro, Hertford County, North Carolina. 37 feet (11.3 m) of section exposed; sample 1 foot (30 cm) above base of 3-foot (91-cm) bluish clayey sand unit at base of section. T. Gibson, 1959.

25950. St. Marys Formation. Bluff ¼ mile (1.2 km) south of Little Cove Point on western shore of Chesapeake Bay, Calvert County, Maryland. 46 feet (14 m) of section exposed; sample 1 foot (30 cm) above base of 5-foot (1.5-m) bluish sandy clay unit that extends from 11 to 16 feet (3.4 to 4.9 m) above base of section. T. Gibson, 1959.

25955. St. Marys Formation. Langleys Bluff, 5½ miles (8.8 km) south of Cedar Point on western shore of Chesapeake Bay, St. Marys County, Maryland. 2½ feet (76 cm) of section exposed; lowest 6 inches (15 cm) of bluish sandy clay contains scattered fossils, upper 2 feet (61 cm) of yellow sandy clay contains concentrated fossil bands; sample 2½ feet (76 cm) above beach. T. Gibson, 1959.

25957. St. Marys Formation. Small bluff ¼ mile (0.4 km) SE of Chancellor Point, St. Marys River, St. Marys County, Maryland. 7.5 (2.3 m) feet of section exposed; sample 6 inches (15 cm) above base of 2-foot (61-cm) bluish sandy clay unit, which is at base of section. T. Gibson, 1959.

25960. Choptank Formation. Bluff ½ mile (0.8 km) south of Flag Pond on western shore of Chesapeake Bay, Calvert County, Maryland. 105 feet (32 m) of section exposed; sample 2 feet (61 cm) above base of 15-foot (4.6-m) unit of fossiliferous sand (zone 19), which extends from 17 to 32 feet (5.2 to 9.8 m) above base of section. T. Gibson, 1959.

25962. (same formation/location as 25960); sample 1 foot (30 cm) above base of 2 feet (61 cm) of bluish green sand exposed to base of section at beach level (zone 17). T. Gibson, 1959.

25965. Choptank Formation. Nomini Cliffs, 12.5 miles (2.4 km) west of eastern end of cliffs, on Potomac River, Westmoreland County, Virginia. 70 feet (21 m) of section exposed; sample 25 feet (7.6 m) above base of 30-feet (9.1-m) unit of bluish sandy clay which is at base of section. T. Gibson, 1959.

25966. Paynes Hammock Formation. Stop 6, 1975 GCAGS Guidebook. Exposure along western bank of Chickasawhay River, about 200 feet (61 m) north of U.S. Highway 84 bridge about 2.5 miles (4 km) west of center of downtown Waynesboro, Mississippi; sample in bed 12 of measured section, about 3.5 feet (1.1 m) above the contact with the underlying Chickasawhay Formation. L. Bybell, R. Christopher, and C. Smith, 25 October 1975.

25969. Calvert Formation. Bluff ¼ mile (0.4 km) south of Governor's Run on western shore of Chesapeake Bay in Calvert County, Maryland. 26.5 feet (8.1 m) of section exposed; sample 1.5 feet (46 cm) above base of 3.5-foot (1.1-m) unit of bluish sandy clay, which is at base of section. T. Gibson, 1959.

25971. Calvert Formation. Bluff ½ mile (0.8 km) south of Parker Creek on western shore of Chesapeake Bay, Calvert County, Maryland. 30 feet (9.1 m) of section exposed; sample in middle of 1-foot (30-cm) unit of blue sandy clay, fossiliferous, which extends from 4 to 5 feet (122–152 cm) above base of section (zone 12). T. Gibson, 1959.

25972. (same formation/location as 25971); sample 2.5 feet (76 cm) above base of 4-foot (122-cm) blue clay unit at base of section (zone 11). T. Gibson, 1959.

25974. Calvert Formation. Bluff 1 mile (1.6 km) south of

Plum Point on western shore of Chesapeake Bay, Calvert County, Maryland: sample 2 feet (61 cm) above beach level in 7 feet (2.1 m) of greenish fossiliferous sand of zone 10. T. Gibson, 1959.

25975. Calvert Formation. Bluff 1 mile (1.6 km) north of Plum Point on western shore of Chesapeake Bay, Calvert County, Maryland. 28.5 feet (8.7 m) of section exposed: sample 1 foot (30 cm) above base of 10-foot (3-m) unit of fossiliferous sand (zone 10), which extends 18.5 to 28.5 feet (5.6 to 8.7 m) above base of section. T. Gibson, 1959.

25977. (same formation/location as 25975); sample 6 feet (1.8 m) above base of 10-foot (3-m) unit of bluish green clayey sand (zone 8), which extends from 6 to 16 feet (1.8 to 4.9 m) above base of section. T. Gibson, 1959.

25980. Calvert Formation. Bluff south of Chesapeake Beach at Randle Cliffs Community Association Church, western shore of Chesapeake Bay, Calvert County, Maryland: sample 8 feet (2.4 m) above *Ostrea percrassa* bed (zone 4), 1 foot (30 cm) above base of thickly packed *Corbula* bed 3 feet (91 cm) thick. T. Gibson, J. Ayres, 1 July 1963.

25981. (same formation/location as 25980); sample in diatomaceous sediments, 4 feet (122 cm) below *Ostrea percrassa* bed. T. Gibson, J. Ayres, 1 July 1963.

25982. Calvert Formation. Bluffs about 1.5 miles (2.4 km) south of Plum Point on western shore of Chesapeake Bay, Calvert County, Maryland. 2 feet (61 cm) of bed 10 exposed above beach level: sample 1 foot (30 cm) below top of bed 10. T. Gibson, J. Ayres, 1 July 1963.

25983. St. Marys Formation. Bluff at Windmill Point on west side of St. Marys River, St. Marys County, Maryland. 5 feet (1.5 m) of section exposed in bank; sample 1 foot (30 cm) above base of 4-foot (122-cm) blue clayey sand unit, which is at base of section. T. Gibson, J. Ayres, 1 July 1963.

25985. Choptank Formation. Section at step area at Baltimore Gas and Electric Company Nuclear Power Plant site south of St. Leonards, Calvert County, Maryland, on western shore of Chesapeake Bay. Sample taken 1 foot (30 cm) below top of zone 17. T. Gibson, 1969.

25989. Waccamaw Formation. Pierce Bros. marl pit, about 3 miles (4.8 km) west of Town Creek on road to Winnabow, Brunswick County, North Carolina. 6.5 feet (2 m) of section exposed; sample 1 foot (30 cm) below top of 3-foot (91-cm) blue sand unit, which extends to water level. T. Gibson, D. Wilson, 22 June 1963.

25992. Pungo River Formation. Gatesville Well, North Carolina; hole located on south end of Gatesville, Gates County: sample at 131.5 feet (40.1 m) below well collar. T. Gibson and others, 1967.

25993. (same formation/location as 25992); sample 138.0 feet (42.1 m) below well collar. T. Gibson and others, 1967.

25995. "Yorktown" Formation. Texasgulf Inc. Lee Creek Mine; NW wall of test pit, Beaufort County, North Carolina. 21 feet (6.4 m) of section at top of pit; sample 1 foot (30 cm) below top of 3- to 4-foot (92-122-cm) greenish blue clayey sand unit which is 2 feet (61 cm) below top of section; top of section marked by brown cross-bedded sand. T. Gibson, 5 December 1963.

25997. (same formation/location as 25995); sample 5 feet (1.5 m) below top of 6- to 7-foot (1.8–2.1-m) blue clayey sand unit, which extends from 7 to 14 feet (2.1 to 4.3 m) below top of section. T. Gibson, 5 December 1963.

26001. "Yorktown" Formation. Moores Bridge Well, Moores Bridge Pumping Station, Norfolk, Virginia; sample 112.5 feet (34.3 m) below collar, blue-green clayey fine sand, fossiliferous. T. Gibson, 1967.

26002. Pungo River Formation. (same location as 26001); sample 581 feet (177.1 m) below collar, dark olive-green silty clay. T. Gibson, 1967.

26003. (same formation/location as 26002); sample 610 feet (239.3 m) below collar, olive-green phosphatic sand. T. Gibson, 1967.

26009. Yorktown Formation. Texasgulf Inc. Lee Creek Mine, NW wall of test pit, Beaufort County, North Carolina; sample 6 feet (1.8 m) below top of 10-foot (3-m) unit of blue clayey sand which extends from 1 to 11 feet (0.3 to 3.4 m) above base of Yorktown Formation. T. Gibson, 1963.

26010. (same formation/location as 26009); sample 9 inches (22.9 cm) below top of 1-foot (30-cm) blue sand unit containing *Placopecten clintonius*, which is lowest unit of Yorktown Formation. T. Gibson, 1963.

26012. Pungo River Formation. (same location as 26009); sample 5 feet (1.5 m) below top of 6-foot (1.8-m) yellow-green shell hash and phosphatic sand unit, which is at top of Pungo River Formation. T. Gibson, 1963.

26013. (same formation/location as 26012); sample at base of 6-foot (1.8-m) yellow-green shell hash and phosphatic sand unit, which is at top of Pungo River Formation. T. Gibson, 1963.

26014. (same formation/location as 26012); sample at top of 3-foot (91-cm) unit of interbedded limestone and phosphatic sand beds that extend from 9 to 12 feet (2.3 to 3.7 m) below the top of the Pungo River Formation. T. Gibson, 1963.

26018. Pungo River Formation. Well C181, near Great Lake, Craven County, North Carolina; 48.5 feet (12.6 m) below collar; in unit of 6.5 feet (2 m) of yellow-green sandy shell hash. T. Gibson and others, 1967.

26019. Choptank Formation, Bartein's Landing, Mary-

land. From interior of molluscan shells in Smithsonian USNM collections.

26020. Calvert Formation. Well core at Baltimore Gas and Electric Company Calvert Cliffs Nuclear Power Plant south of St. Leonards, Calvert County, Maryland; sample 43 at 165′10″–166′1″ below (50.5–50.6 m) collar. T. Gibson and F. Whitmore, September 1967.

26021. Waccamaw Formation. Marl pit ½ mile (0.8 km) north of Old Dock, Columbus County, North Carolina; sediment is largely coarse quartz sand; megafossils fairly common. T. Gibson, 1959.

26022. Calvert Formation. Bluff south of Chesapeake Beach at Randle Cliffs Community Association Church, western shore of Chesapeake Bay, Calvert County, Maryland; sample in 7-foot (2.1-m) unit with bands of *Corbula* more common near top; this unit immediately above *Ostrea percrassa* bed and corresponds to zone 5; sample 1 foot (30 cm) above base. T. Gibson, J. Ayres, July 1, 1963.

26023. Calvert Formation. 1 mile (1.6 km) south of Plum Point, Calvert County, Maryland: zone 12. A. Dorsey.

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## PLATE 1

1, 2. *Globigerinoides altiaperturus* Bolli, Calvert Formation, Plum Point, Maryland, USNM 240082, USGS 25975: 1, spiral view; 2, apertural view. Both × 93.

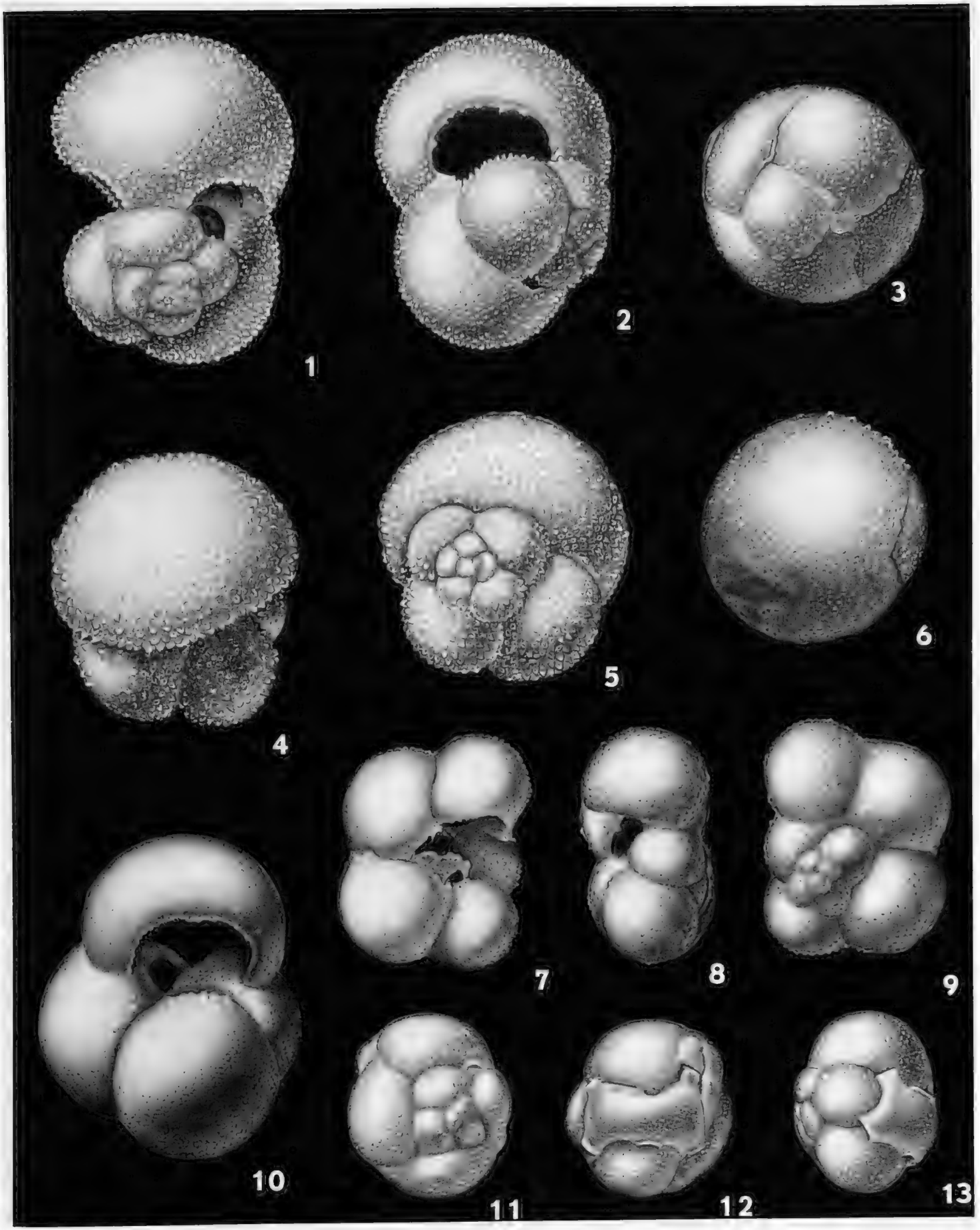
3, 6. *Praeorbulina glomerosa glomerosa* (Blow), Calvert Formation, Plum Point, Maryland, USNM 240083, USGS 25974: 3, spiral view; 6, side view. Both × 93.

4, 5. *Globigerinoides sicanus* de Stefani, Calvert Formation, Parker Creek, Maryland, USNM 240084, USGS 25972: 4, umbilical view; 5, spiral view. Both × 148.

7–9. *Globigerina praebulloides pseudociperoensis* Blow, Calvert Formation, Plum Point, Maryland, USNM 240086, USGS 25975: 7, umbilical view; 8, edge view; 9, spiral view. All × 93.

10. *Globigerina apertura* Cushman, Yorktown Formation, Suffolk, Virginia, USNM 240085, USGS 25941: umbilical view, × 150.

11–13. *Globigerinita glutinata ambitacrena* (Loeblich and Tappan), Yorktown Formation, near Murfreesboro, North Carolina, USNM 240087, USGS 25948: 11, spiral view; 12, umbilical view; 13, side view. All × 93.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## PLATE 2

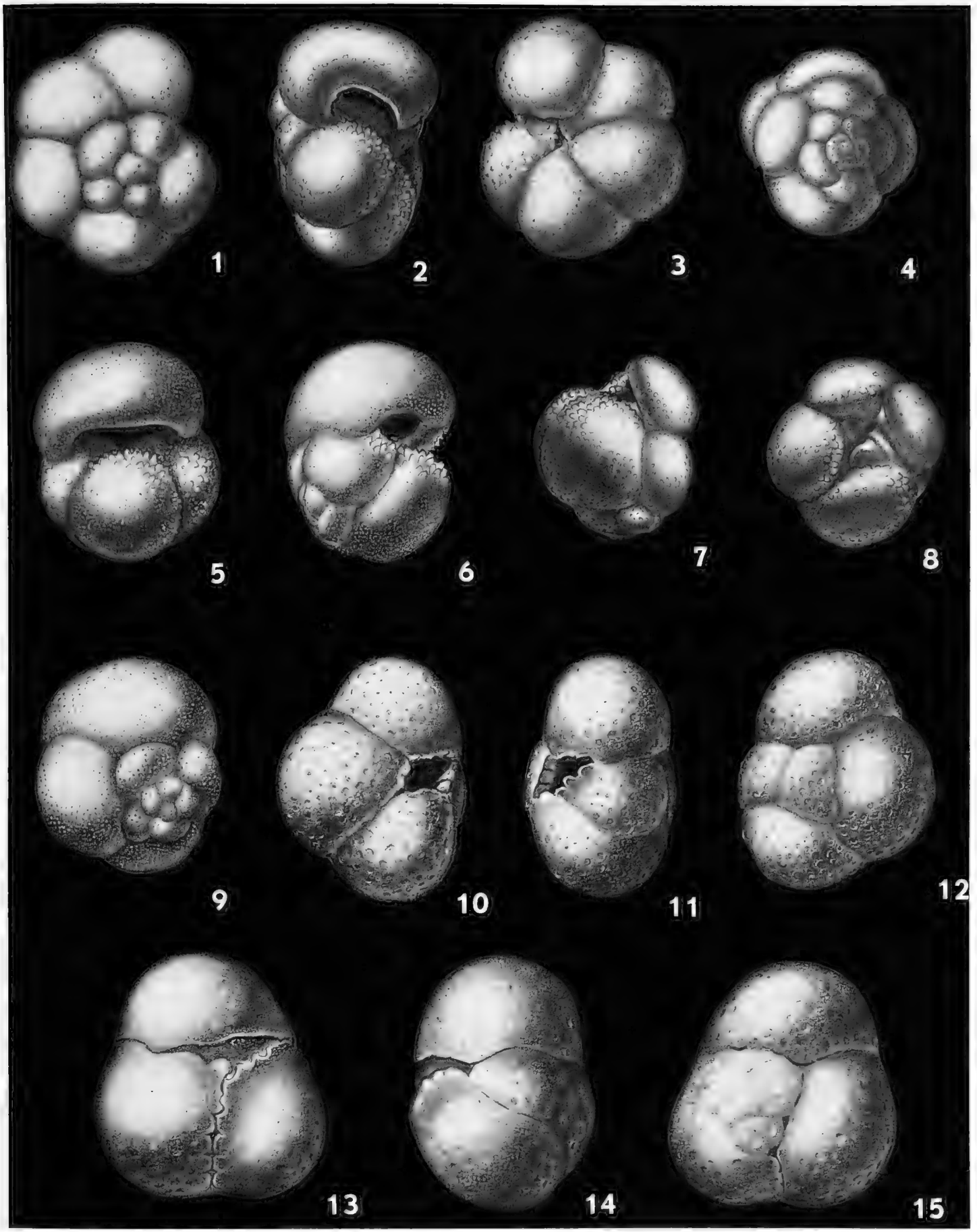
1–3. "*Turborotalia*" *acostaensis humerosa* (Takayanagi and Saito), Yorktown Formation, near Murfreesboro, North Carolina, USNM 240088, USGS 25948: 1, spiral view; 2, edge view; 3, umbilical view. All × 93.

4, 7, 8. *Globoquadrina altispira altispira* (Cushman and Jarvis), Yorktown Formation, near Murfreesboro, North Carolina, USNM 240089, USGS 25948: 4, spiral view; 7, edge view; 8, umbilical view. All × 93.

5, 6, 9. *Pulleniatina obliquiloculata obliquiloculata* (Parker and Jones), Yorktown Formation, Black Rock Landing, Bertie County, North Carolina, USNM 240090, USGS 25929: 5, umbilical view; 6, edge view; 9, spiral view. All × 93.

10–12. *Sphaeroidinellopsis seminulina seminulina* (Schwager), Yorktown Formation, near Murfreesboro, North Carolina, USNM 240091, USGS 25948: 10, umbilical view; 11, edge view; 12, spiral view. All × 93.

13–15. *Sphaeroidinellopsis subdehiscens subdehiscens* (Blow), Yorktown Formation, near Murfreesboro, North Carolina, USNM 240092, USGS 25948: 13, umbilical view; 14, edge view; 15, spiral view. All × 93.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## PLATE 3

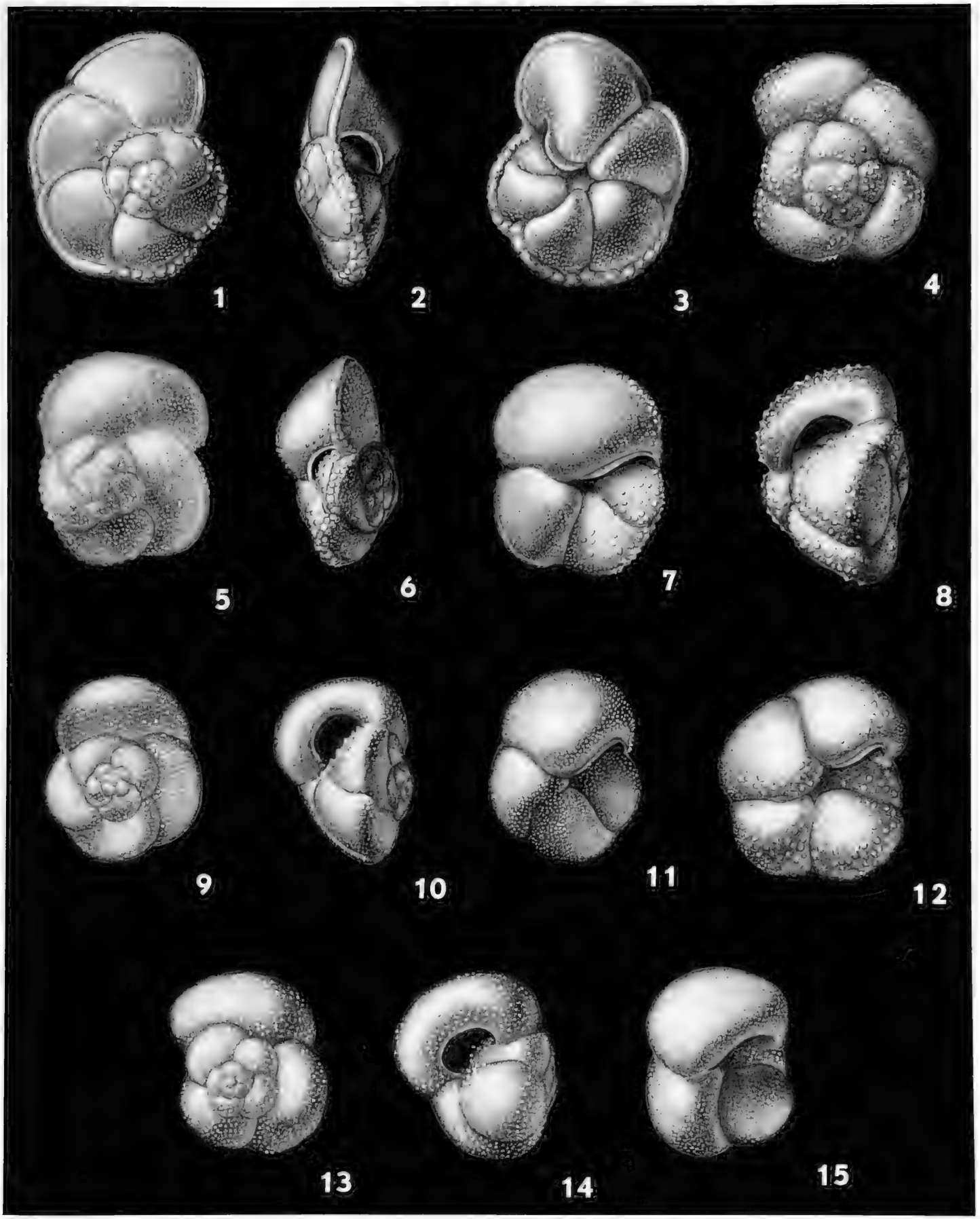
1–3. *Globorotalia menardii* (Parker, Jones, and Brady), Yorktown Formation, Suffolk, Virginia, USNM 240093, USGS 25941: 1, spiral view; 2, edge view; 3, umbilical view. All × 93.

4, 8, 12. *Globorotalia* species cf. *G. crassula* Cushman and Stewart, Yorktown Formation, near Murfreesboro, North Carolina, USNM 240094, USGS 25948: 4, spiral view; 8, edge view; 12, umbilical view. All × 93.

5–7. *Globorotalia hirsuta hirsuta* (d'Orbigny), Yorktown Formation, Yorktown, Virginia, USNM 240095, USGS 25934: 5, spiral view; 6, edge view; 7, umbilical view. All × 93.

9–11. *Globorotalia puncticulata* (Deshayes), Yorktown Formation, near Murfreesboro, North Carolina, USNM 240096, USGS 25948: 9, spiral view; 10, edge view; 11, umbilical view. All × 93.

13–15. "*Turborotalia*" *inflata* (d'Orbigny), Waccamaw Formation, Walker's Bluff, North Carolina, USNM 240097, USGS 25925: 13, spiral view; 14, edge view; 15, umbilical view. All × 93.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## PLATE 4

1–6. "*Turborotalia*" *birnageae* (Blow), Pungo River Formation, Lee Creek Mine, North Carolina: 1, USNM 240098, USGS 26013, umbilical view, × 440; 2, USNM 240099, USGS 26013, umbilical view, × 400; 3, USNM 240100, USGS 26012; umbilical view, × 300; 4, USNM 240101, USGS 26013, umbilical view, × 300; 5, USNM 240102, USGS 26012, edge view, × 450; 6, USNM 240102, USGS 26012, umbilical view, × 410.

7, 8. *Globigerinoides altiaperturus* Bolli, Pungo River Formation, Lee Creek Mine, North Carolina: 7, USNM 240103, USGS 26012, umbilical view, × 290; 8, USNM 240104, USGS 26013, umbilical view, × 290.

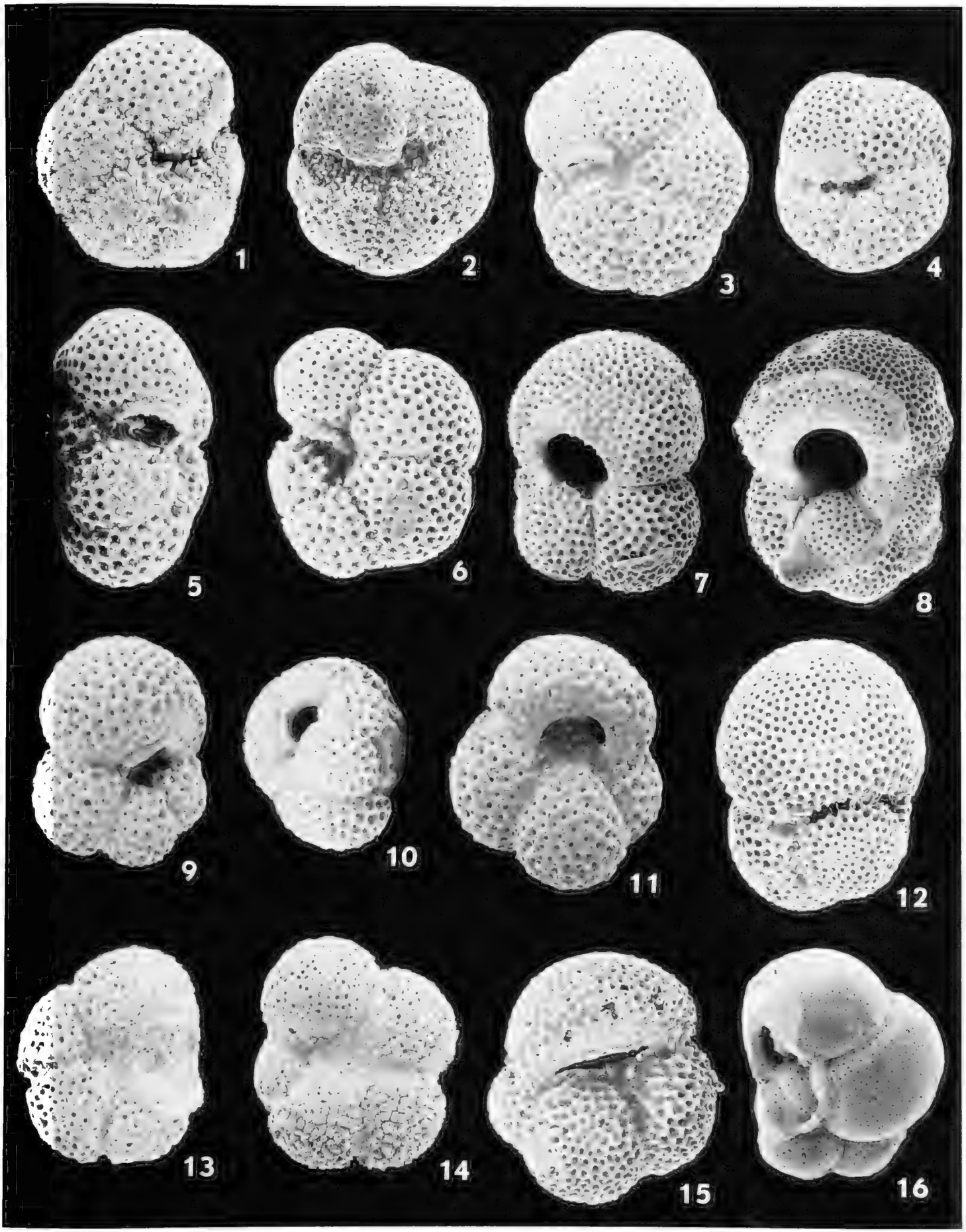
9–11. *Globigerina woodi woodi* Jenkins, Pungo River Formation, Lee Creek Mine, North Carolina, USGS 26013: 9, USNM 240105, umbilical view; 10, USNM 240105, edge view; 11, USNM 240106, umbilical view. All × 300.

12. *Globigerinoides trilobus trilobus* (Reuss), Pungo River Formation, Lee Creek Mine, North Carolina, USNM 240107, USGS 26012, umbilical view, × 240.

13, 14. *Globigerina* species cf. *G. angulifficinalis* Blow, Pungo River Formation, Lee Creek Mine, North Carolina: 13, USNM 240108, USGS 26012, umbilical view, × 300; 14, USNM 240109, USGS 26013, umbilical view, × 300.

15. *Globigerina euapertura* Jenkins, Pungo River Formation, Lee Creek Mine, North Carolina, USNM 240110, USGS 26012, umbilical view, × 300.

16. *Cassigerinella chipolensis* (Cushman and Ponton), Pungo River Formation, Lee Creek Mine, North Carolina, USNM 240111, USGS 26013, side view, × 400.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## PLATE 5

1, 2. *Globorotalia scitula praescitula* Blow, Pungo River Formation, Lee Creek Mine, North Carolina, USNM 240112, USGS 26012: 1, side view, × 420; 2, umbilical view, × 410.

3, 4. *Globorotalia scitula praescitula* Blow, Pungo River Formation, Lee Creek Mine, North Carolina, USNM 240113, USGS 26012: 3, umbilical view, × 330; 4, side view, × 360.

5, 6. *Globorotalia peripheroronda* Blow and Banner, Pungo River Formation, Lee Creek Mine, North Carolina, USNM 240114, USGS 26012: 5, umbilical view, × 410; 6, side view, × 450.

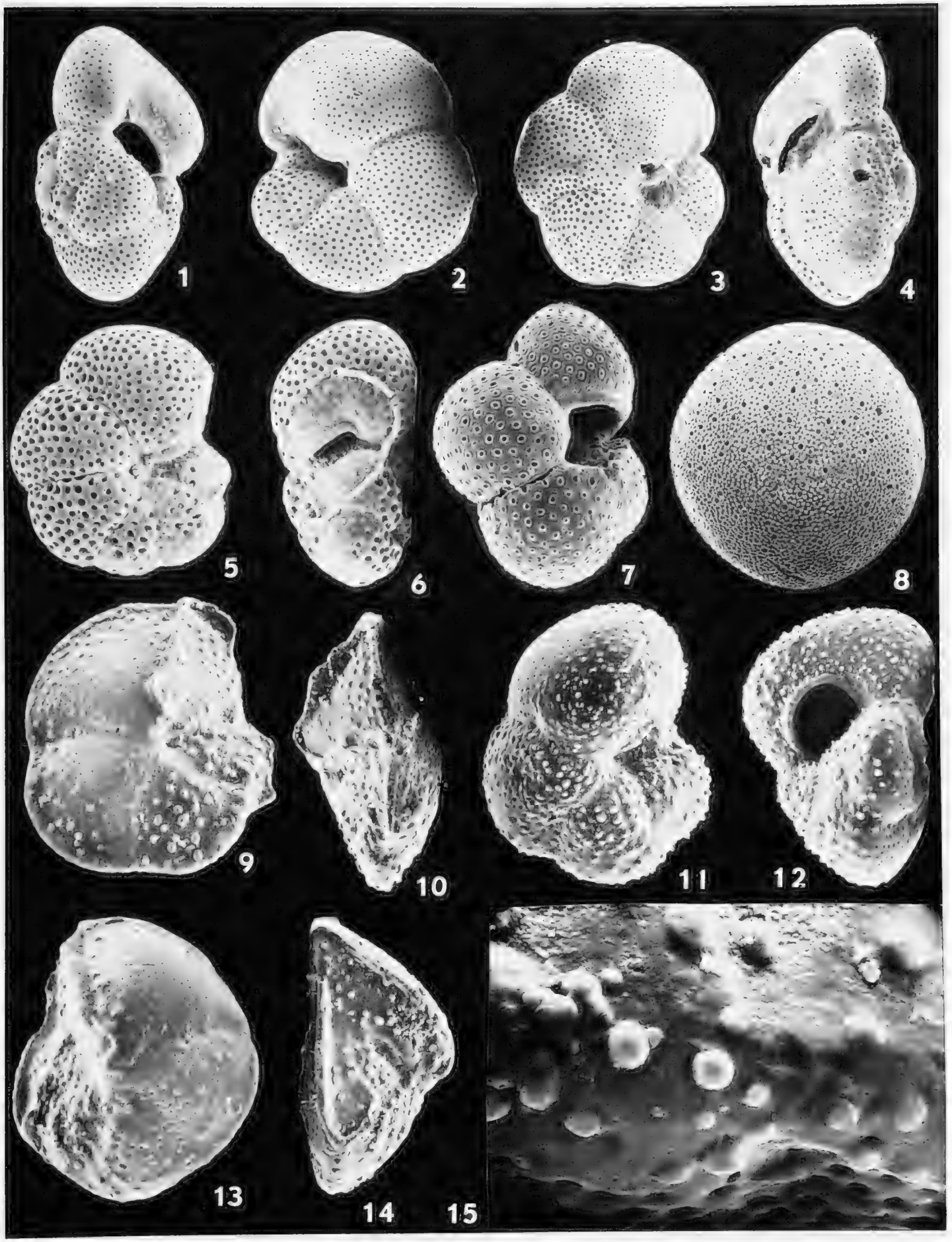
7. *Sphaeroidinellopsis seminulina seminulina* (Schwager), Pungo River Formation, Gatesville, North Carolina well core, USNM 240115, USGS 25992, umibilical view, × 170.

8. *Orbulina universa* d'Orbigny, Pungo River Formation, Gatesville, North Carolina well core, USNM 240116, USGS 25992, × 77.

9–10. *Globorotalia hirsuta hirsuta* (d'Orbigny), Croatan Formation, Lee Creek Mine, North Carolina, USNM 240117, USGS 25995: 9, umbilical view; 10, side view. Both × 300.

11, 12. *Globorotalia puncticulata* (Deshayes), Yorktown Formation, Lee Creek Mine, North Carolina, USNM 240118, USGS 26009: 11, umbilical view; 12, side view. Both × 270.

13–15. *Globorotalia* species cf. *G. truncatulinoides truncatulinoides* (d'Orbigny), Croatan Formation, Lee Creek Mine, North Carolina, USNM 240119, USGS 25995: 13, umbilical view, × 300; 14, side view, × 300; 15, close-up of periphery, × 1375.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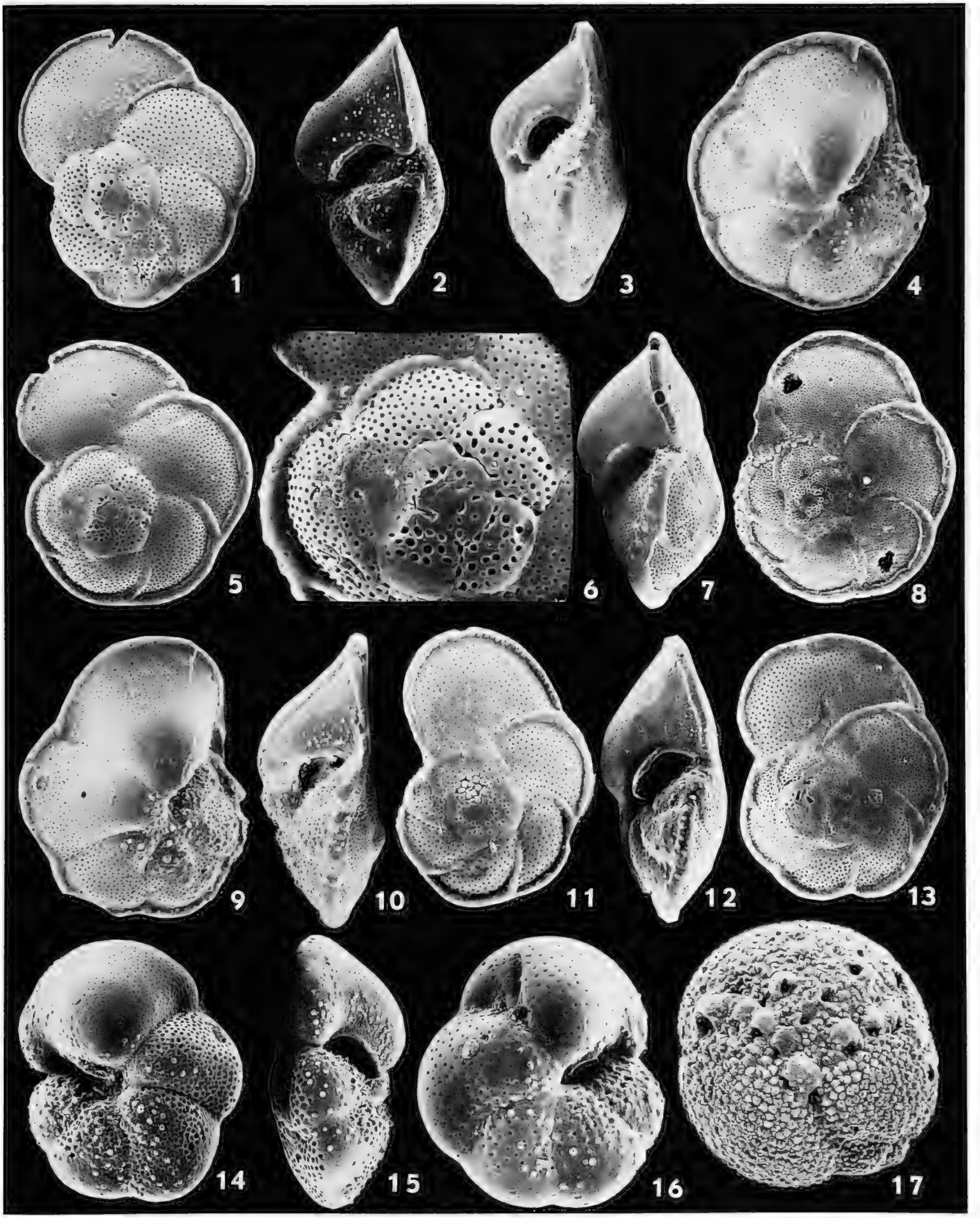
## PLATE 6

1–13. *Globorotalia merotumida* Blow and Banner, "Virginia St. Marys" beds, Gatesville Well, North Carolina, USGS 25992: 1, USNM 240120, spiral view, × 260; 2, USNM 240120, side view, × 250; 3, USNM 240121, side view, × 250; 4, USNM 240121, umbilical view, × 250; 5, USNM 240122, spiral view, × 190; 6, USNM 240122, close-up of spiral side, × 490; 7, USNM 240122, side view, × 240; 8, USNM 240123, spiral view, × 250; 9, USNM 240124, umbilical view, × 190; 10, USNM 240124, side view, × 200; 11, USNM 240125, spiral view, × 170; 12, USNM 240125, side view, × 170; 13, USNM 240126, spiral view, × 170.

14, 15. *Globorotalia minima* Akers, "Virginia St. Marys" beds, Gatesville, North Carolina, well core, USNM 240127, USGS 25992: 14, umbilical view, × 340; 15, side view; × 340.

16. *Globorotalia minima* Akers, "Virginia St. Marys" beds, Gatesville, North Carolina, well core, USNM 240128, USGS 25992, umbilical view, × 340.

17. *Globigerinatella insueta* Cushman and Stainforth, Pungo River Formation, Norfolk, Virginia, Moores Bridge Well, USNM 240129, USGS 26002, umbilical view, × 220.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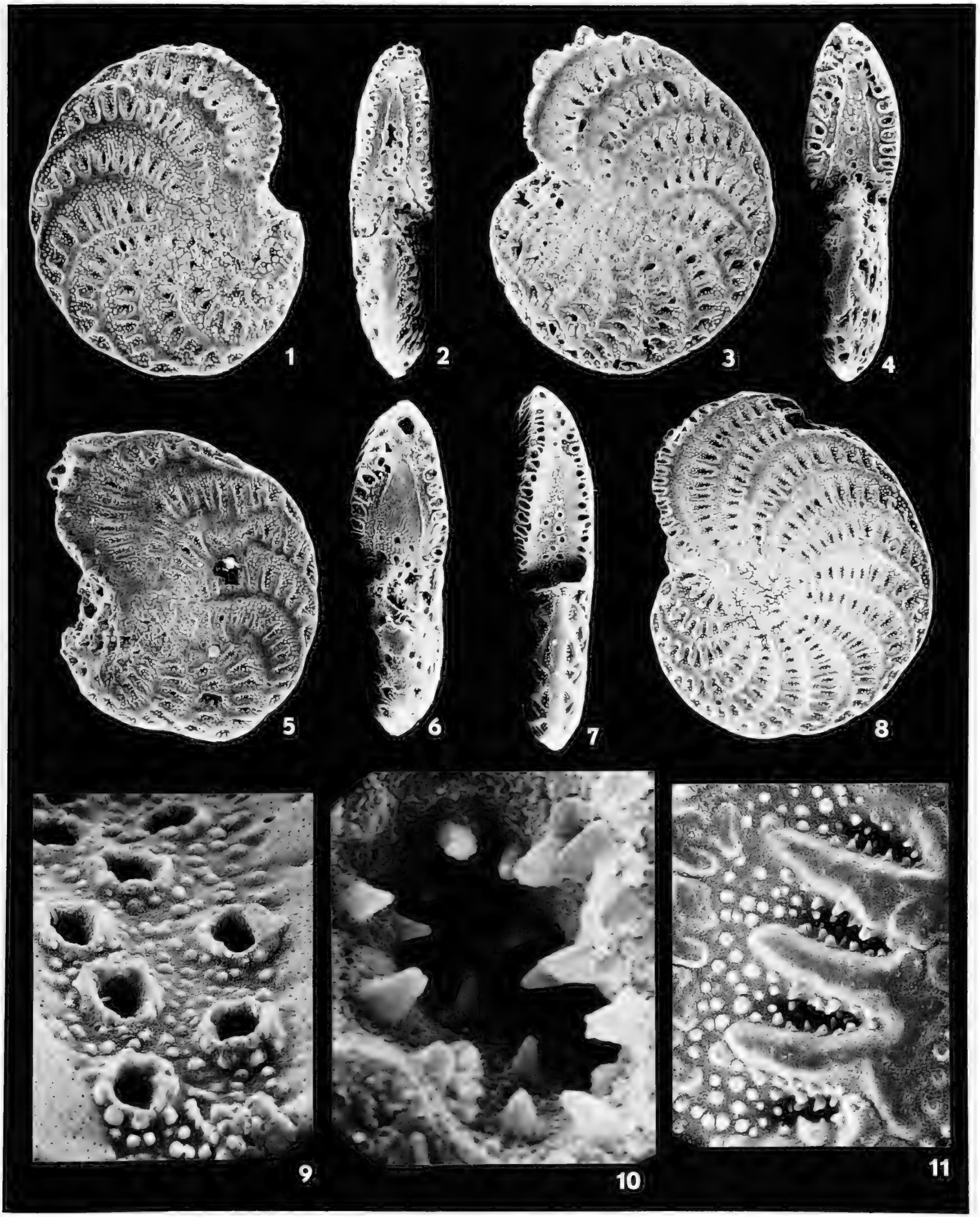
## PLATE 7

*Elphidium neocrespinae*, new species, Croatan Formation, Lee Creek Mine, North Carolina, USGS 25997

1, 2. Paratype, USNM 240130: 1, side view; 2, apertural view. Both × 190.
3, 4. Paratype, USNM 240131: 3, side view; 4, apertural view. Both × 160.
5, 6. Paratype, USNM 240132: 5, side view; 6, apertural view. Both × 150.
7–11. Holotype, USNM 240133: 7, apertural view, × 150; 8, side view, × 140; 9, close-up of apertural face, × 1200; 10, close-up of canal in penultimate chamber, × 6000; 11, close-up of penultimate chamber, × 1000.

Micrographs reduced to 65½% for publication.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## PLATE 8

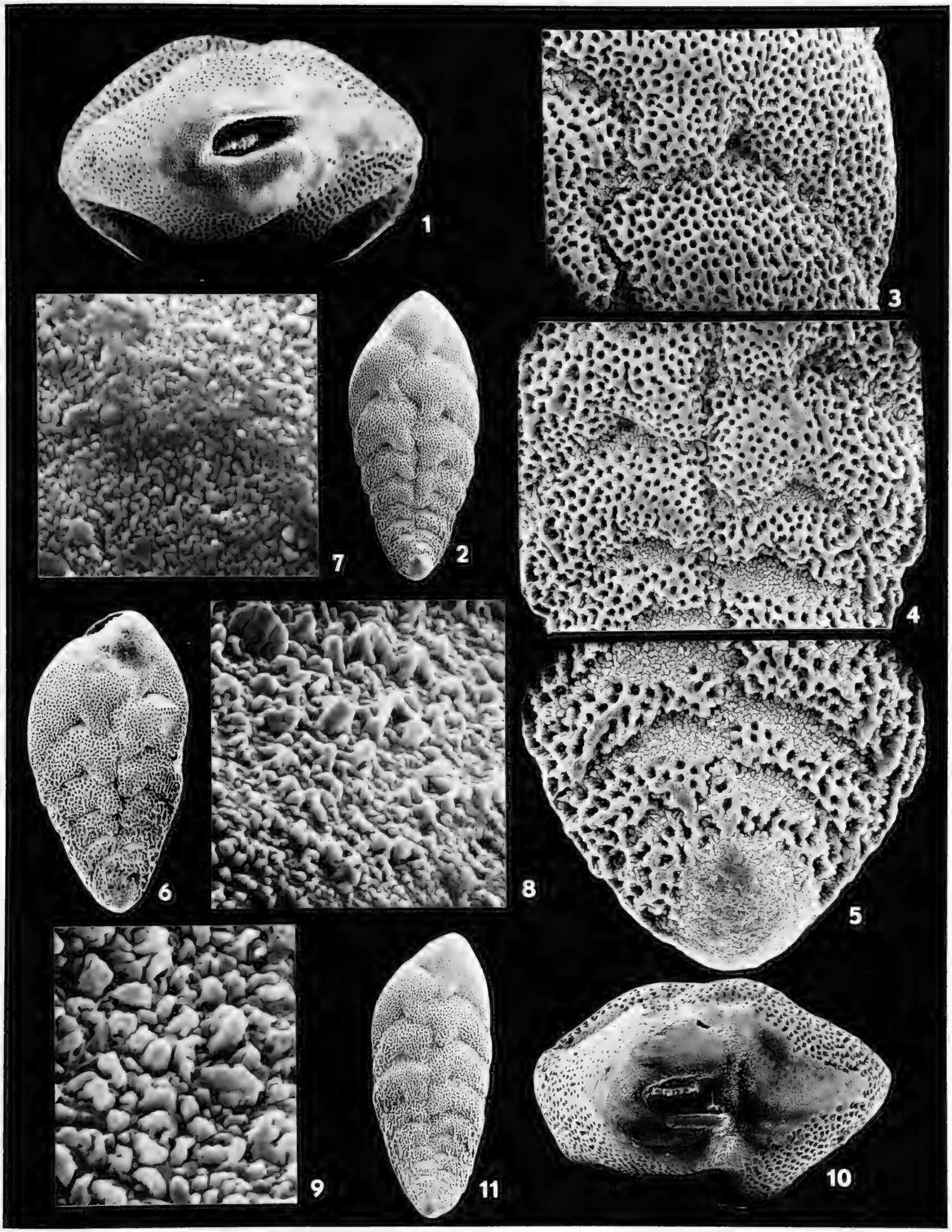
*Bolivina pungoensis*, new species, Pungo River Formation, Lee Creek mine, North Carolina

1–5. Holotype, USNM 240134, USGS 26013: 1, apertural view, × 435; 2, side view, × 150; 3, upper right part of specimen, × 600; 4, lower center part of specimen, × 600; 5, initial part of specimen, × 750.

6–10. Paratype, USNM 240135, USGS 26014: 6, side view, × 200; 7, close-up of apertural face, × 6000; 8, imperforate area of third last chamber, × 6000; 9, imperforate area in fourth chamber of test, × 6000; 10, apertural view, × 410.

11. Paratype, USNM 240136, USGS 26013, side view, × 160.

Micrographs reduced to 66½% for publication.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## PLATE 9

1–4. *Bolivina calvertensis* Dorsey, Pungo River Formation, Lee Creek Mine, North Carolina: 1, USNM 240137, USGS 26014, side view, × 140; 2, USNM 240137, USGS 26014, apertural view, × 500; 3, USNM 240138, USGS 26013, side view, × 220; 4, USNM 240139, USGS 26014, side view, × 200.

5, 9. *Spiroplectammina mississippiensis* (Cushman), "Virginia St. Marys" beds, Gatesville Well, North Carolina, USNM 240140, USGS 25992: 5, apertural view, × 75; 9, side view, × 50.

6. *Siphogenerina lamellata* Cushman, Pungo River Formation, USNM 240141, USGS 26013, side view, × 220.

7, 8. *Siphogenerina* sp., Pungo River Formation, Lee Creek Mine, North Carolina, USNM 240142, USGS 26014: 7, side view, × 110; 8, apertural view, × 245.

10–16. *Siphogenerina lamellata* Cushman, Pungo River Formation, USGS 26003: 10, USNM 240143, side view, × 110; 11, USNM 240144, side view, × 100; 12, USNM 240145, side view, × 115; 13, USNM 240146, side view, × 75; 14, USNM 240147, apertural view, × 130; 15, USNM 240145, apical view, × 225; 16, USNM 240146, apical view, × 310.

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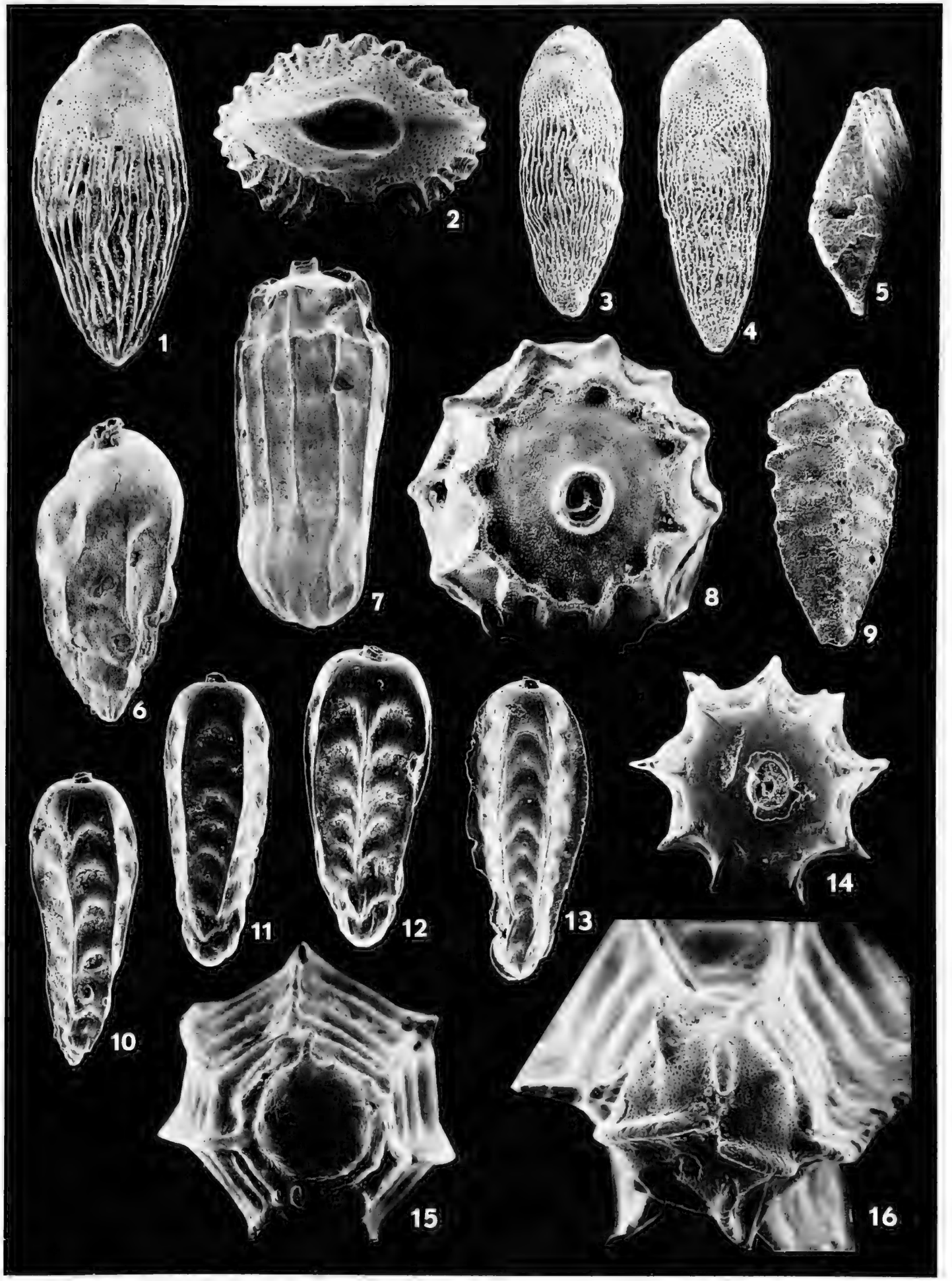
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## PLATE 10

1, 2. *Spiroplectammina exilis* Dorsey, Choptank Formation, Flag Pond, Maryland, USNM 252578, USGS 25985: 1, side view, × 55; 2, apertural view, × 115.

3. *Virgulinella miocenica* (Cushman and Ponton), Pungo River Formation, Lee Creek Mine, North Carolina, USNM 252579, USGS 26013, side view, × 115.

4. *Rosalina cavernata* (Dorsey), Calvert Formation, Baltimore Gas and Electric Company core hole, Calvert County, Maryland, USNM 252580, USGS 26020, umbilical view, × 190.

5, 6, 8. *Cibicides croatanensis*, new species, Croatan Formation, Lee Creek Mine, North Carolina, holotype, USNM 252534, USGS 25997: 5, umbilical view, × 115; 6, side view, × 110; 8, close-up of last chamber on umbilical side, × 800.

7, 10. *Cibicides croatanensis*, new species, Croatan Formation, Lee Creek Mine, North Carolina, paratype, USNM 252535, USGS 25997: 7, spiral view, × 80; 10, close-up of last chamber on spiral side, × 1100.

9. *Praeorbulina glomerosa circularis* (Blow), Calvert Formation Calvert Cliffs, Maryland, USNM 252581, USGS 26023, apical view, × 115.

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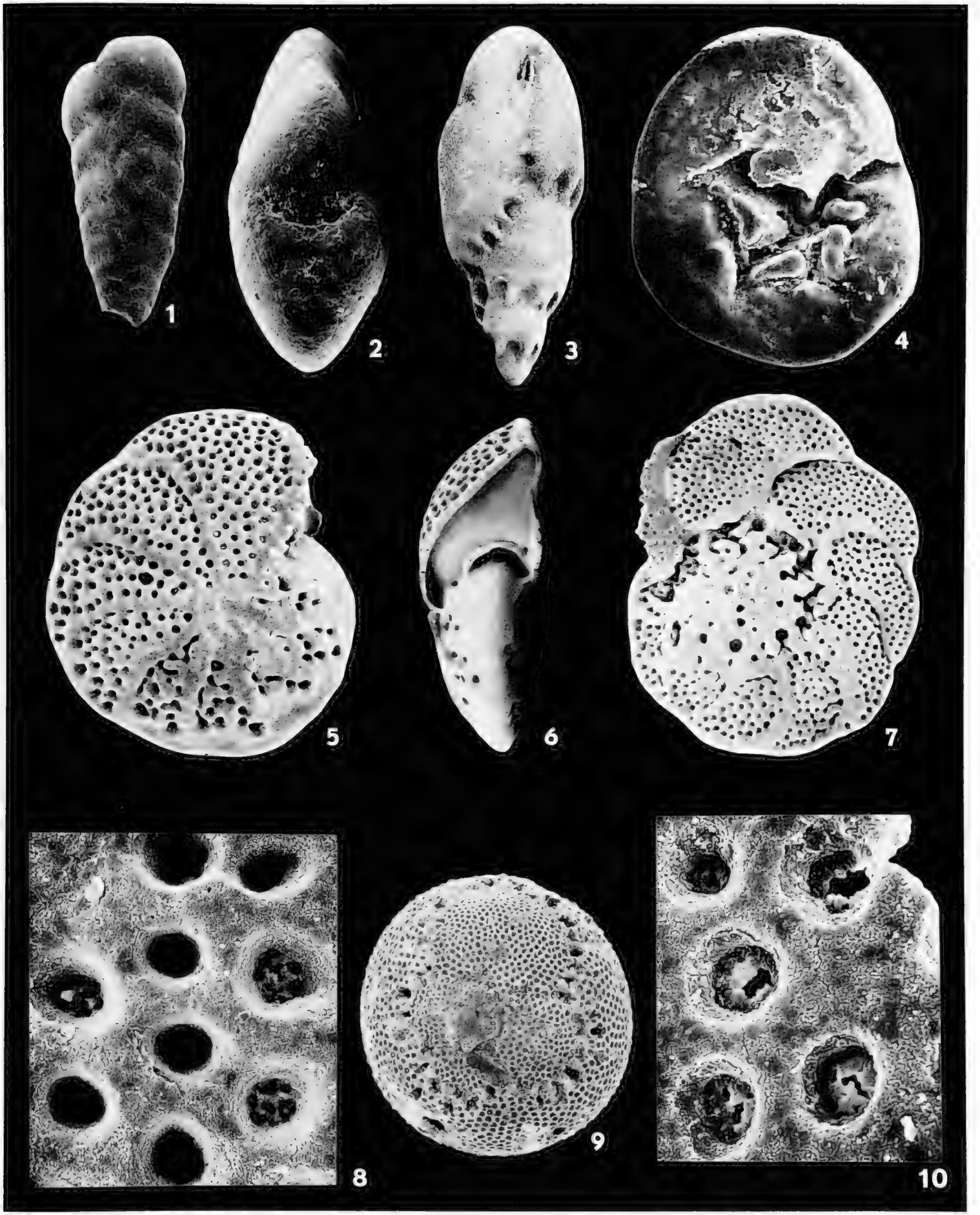
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## PLATE 11

1, 2. *Bolivina marginata multicostata* Cushman, Pungo River Formation, Moores Bridge Well, Norfolk, Virginia, USNM 252582, USGS 26003: 1, apertural view, × 225; 2, side view, × 85.

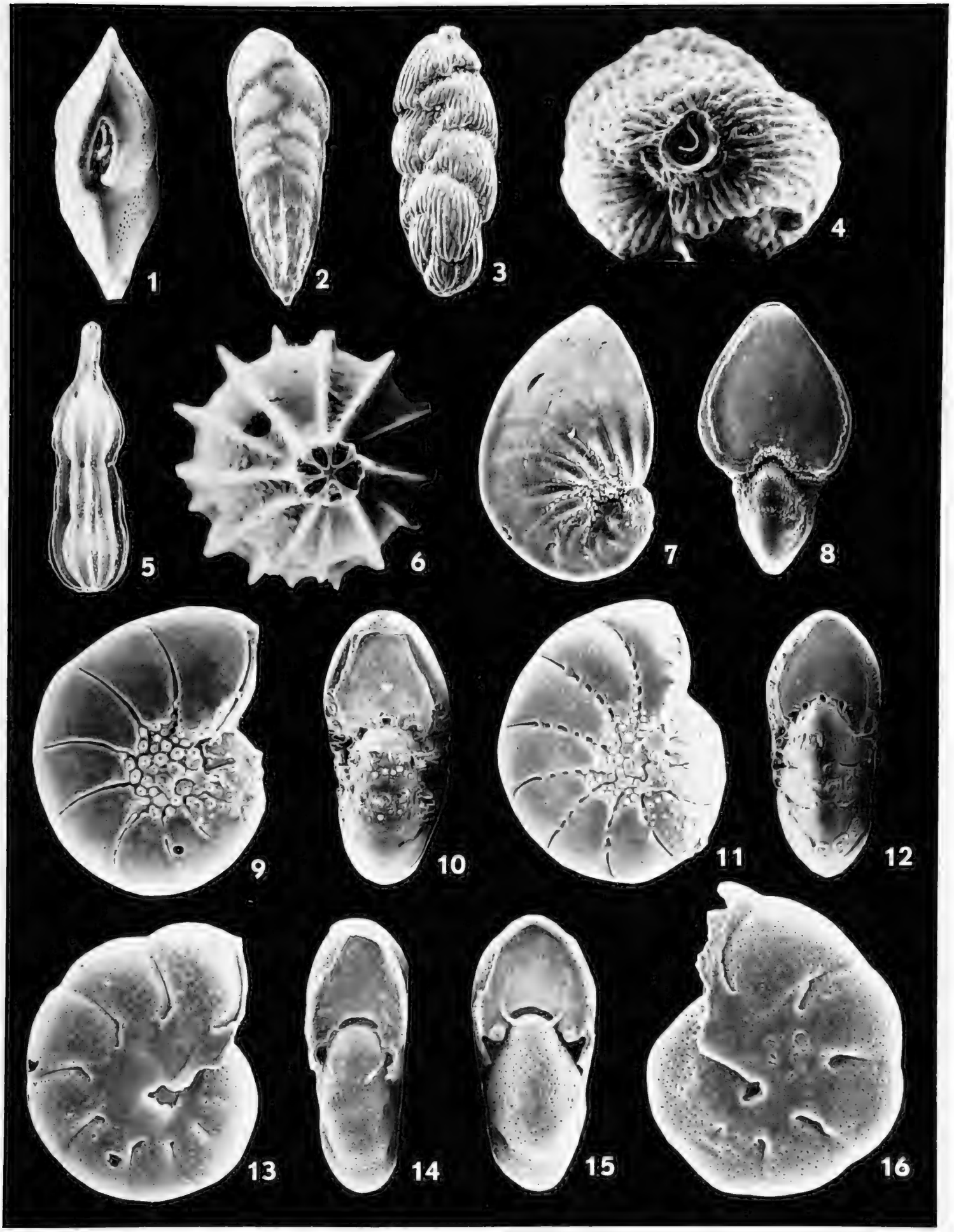
3, 4. *Hopkinsina bononiensis* (Fornasini), "Virginia St. Marys" beds, Gatesville Well, North Carolina, USNM 252583, USGS 25992: 3, side view, × 90; 4, apertural view, × 265.

5, 6. *Nodosaria catesbyi* d'Orbigny, "Virginia St. Marys" beds, Gatesville Well, North Carolina, USNM 252584, USGS 25992: 5, side view, × 75; 6, apertural view, × 260.

7, 8. *Florilus chesapeakensis*, new species, "Virginia St. Marys" beds, Gatesville Well, North Carolina, holotype, USNM 252565, USGS 25992: 7, side view, × 95; 8, apertural view, × 95.

9–12. *Elphidium limatulum* Copeland, Croatan Formation, Lee Creek Mine, North Carolina, USGS 25997: 9, USNM 252586, side view, × 140; 10, USNM 252586, apertural view, × 140; 11, USNM 252587, side view, × 90; 12, USNM 252587, apertural view, × 80.

13–16. *Astrononion stelligerum* (d'Orbigny), Croatan Formation, Lee Creek Mine, North Carolina, USGS 25997: 13, USNM 252588, side view, × 180; 14, USNM 252589, apertural view, × 230; 15, USNM 252590, apertural view, × 210; 16, USNM 252590, side view, × 320.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## PLATE 12

1, 2. *Astrononiom stelligerum* (d'Orbigny), Croatan Formation, Lee Creek Mine, North Carolina, USNM 252591, USGS 25997: 1, side view, × 155; 2, apertural view, × 155.

3, 4. *Nonion calvertensis*, new species, Calvert Formation, Randle Cliffs, Maryland, holotype, USNM 252554, USGS 25980: 3, side view, × 170; 4, apertural view, × 170.

5–7. *Nonion calvertensis*, new species, Calvert Formation, Randle Cliffs, Maryland, paratypes, USGS 25980: 5, USNM 252555, side view, × 170; 6, USNM 252556, apertural view, × 170; 7, USNM 252557, apertural view, × 170; 8, USNM 252557, side view, × 170.

9–14. *Nonion marylandicum* Dorsey, Choptank Formation, Flag Pond, Maryland, USGS 25985: 9, USNM 252592, side view, × 130; 10, USNM 252592, apertural view, × 130; 11, USNM 252593, side view, × 195; 12, USNM 252593, apertural view, × 195; 13, USNM 252594, side view, × 150; 14, USNM 252594, apertural view, × 130.

15, 16. *Elphidium latispatium pontium*, new subspecies, St. Marys Formation, Langley's Bluff, Maryland, holotype, USNM 252571, USGS 25955: 15, side view, × 110; 16, apertural view, × 110.

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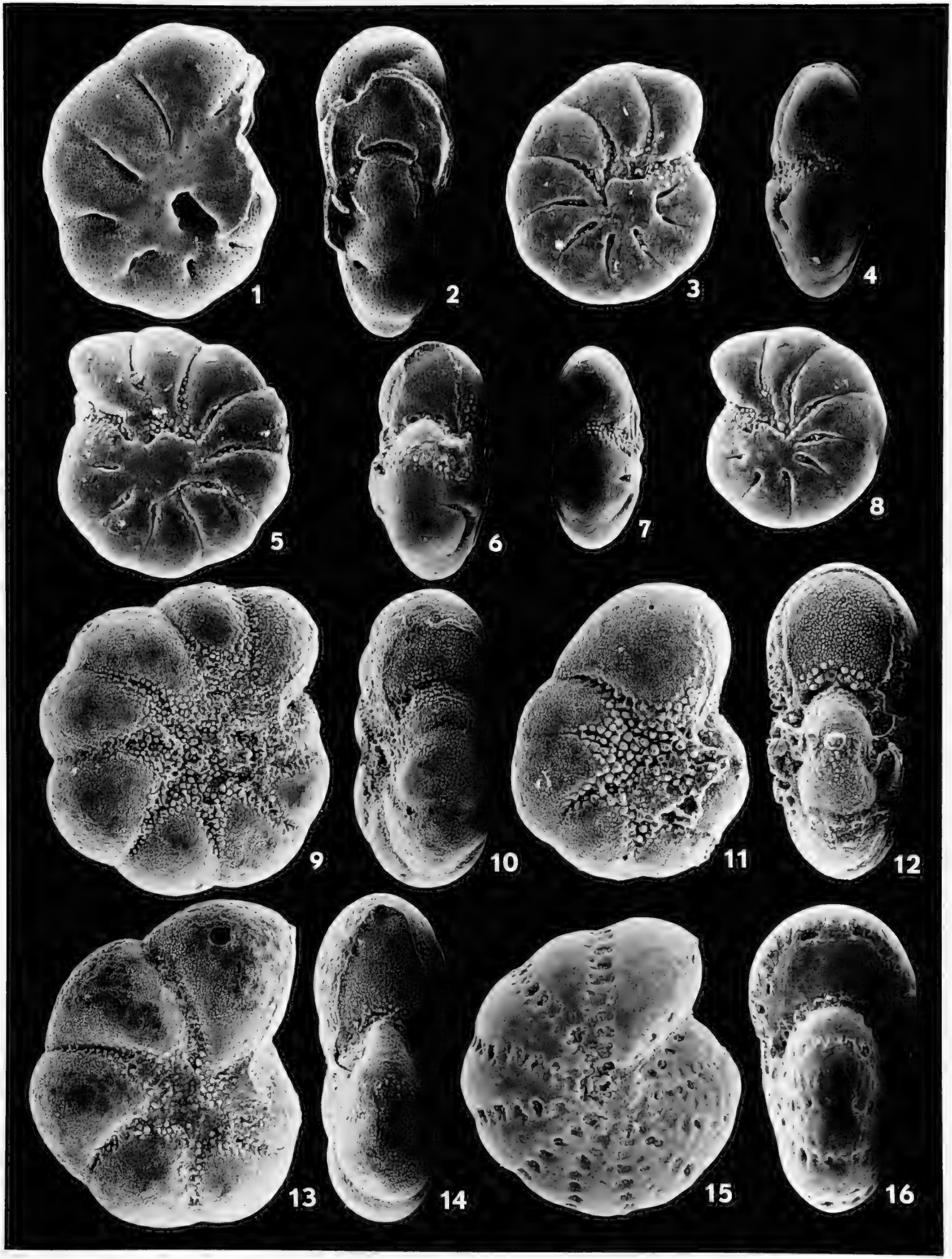
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## PLATE 13

1–5. *Cibicides pungoensis*, new species, "Virginia St. Marys" beds, Gatesville Well, North Carolina, paratypes, USGS 25993: 1, USNM 252542, edge view, × 130; 2, USNM 252542, umbilical view, × 130; 3, USNM 252542, close-up of umbilical side, × 975; 4, USNM 252543, spiral view, × 65; 5, USNM 252544, edge view, × 115.

6, 7, 10. *Cibicides pungoensis*, new species, "Virginia St. Marys" beds, Gatesville Well, North Carolina, holotype, USNM 252541, USGS 25993: 6, umbilical view, × 65; 7, edge view, × 65; 10, close-up of umbilical surface, × 975.

8, 9. *Elphidium latispatium pontium*, new subspecies, St. Marys Formation, Langley's Bluff, Maryland, paratype, USNM 252572, USGS 25955: 8, side view, × 130; 9, apertural view, × 145.

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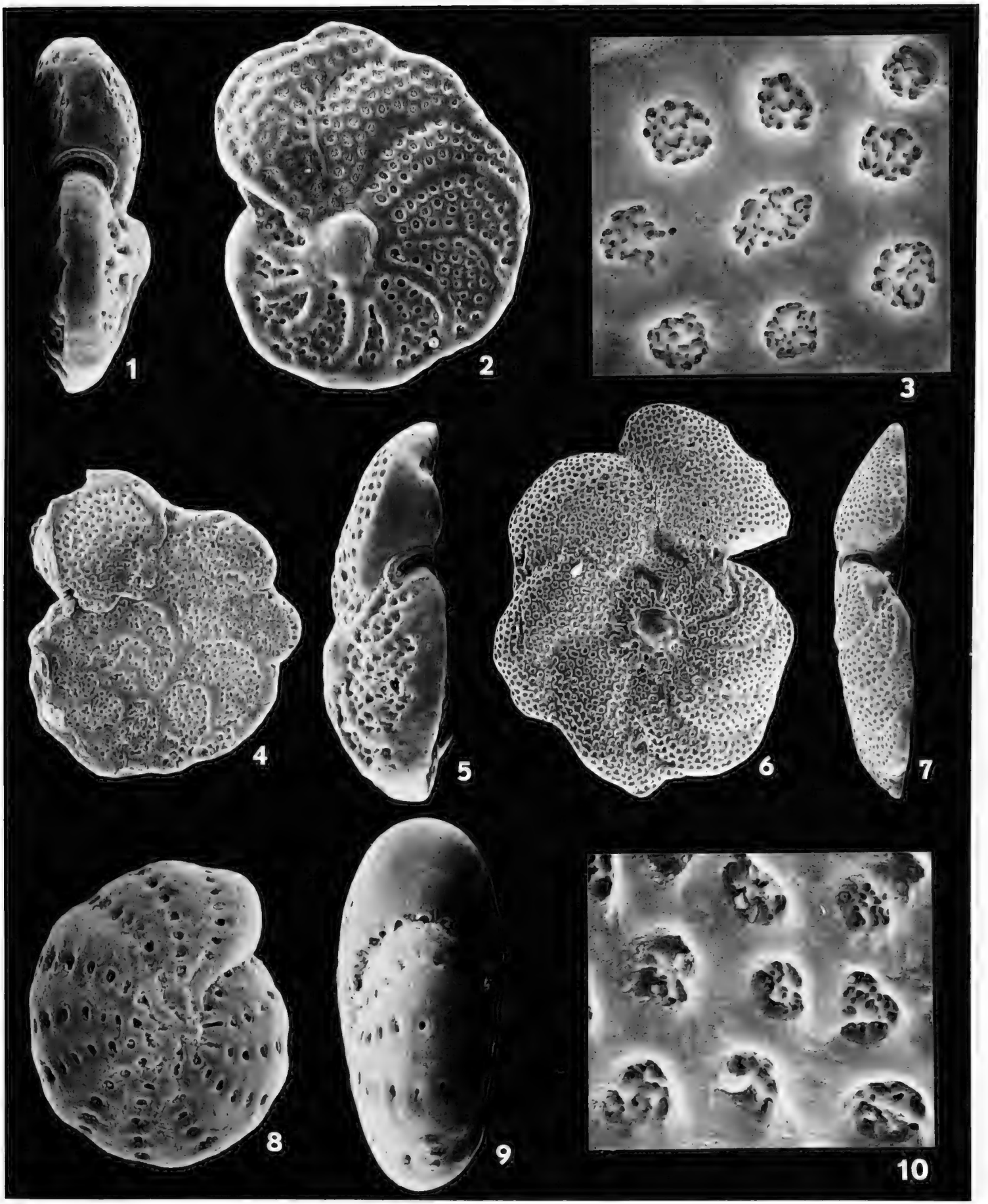
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## PLATE 14

*Cibicides cravenensis*, new species, Pungo River Formation, Great Lake core hole, North Carolina, USGS 26018

1, 2, 5. Paratype, USNM 252528: 1, spiral view, × 90; 2, edge view, × 90; 5, close-up of last chamber on spiral side, × 900.
3, 4, 7. Holotype, USNM 252527: 3, edge view, × 115; 4, umbilical view, × 115; 7, close-up of umbilical side, × 1950.
6. Paratype, USNM 252529, umbilical view, × 65.
8, 9. Paratype, USNM 252530: 8, umbilical view, × 130; 9, close-up of umbilical surface, × 975.
10, 12. Paratype, USNM 252531: 10, edge view; 12, spiral view; both × 65.
11. Paratype, USNM 252532, edge view, × 65.

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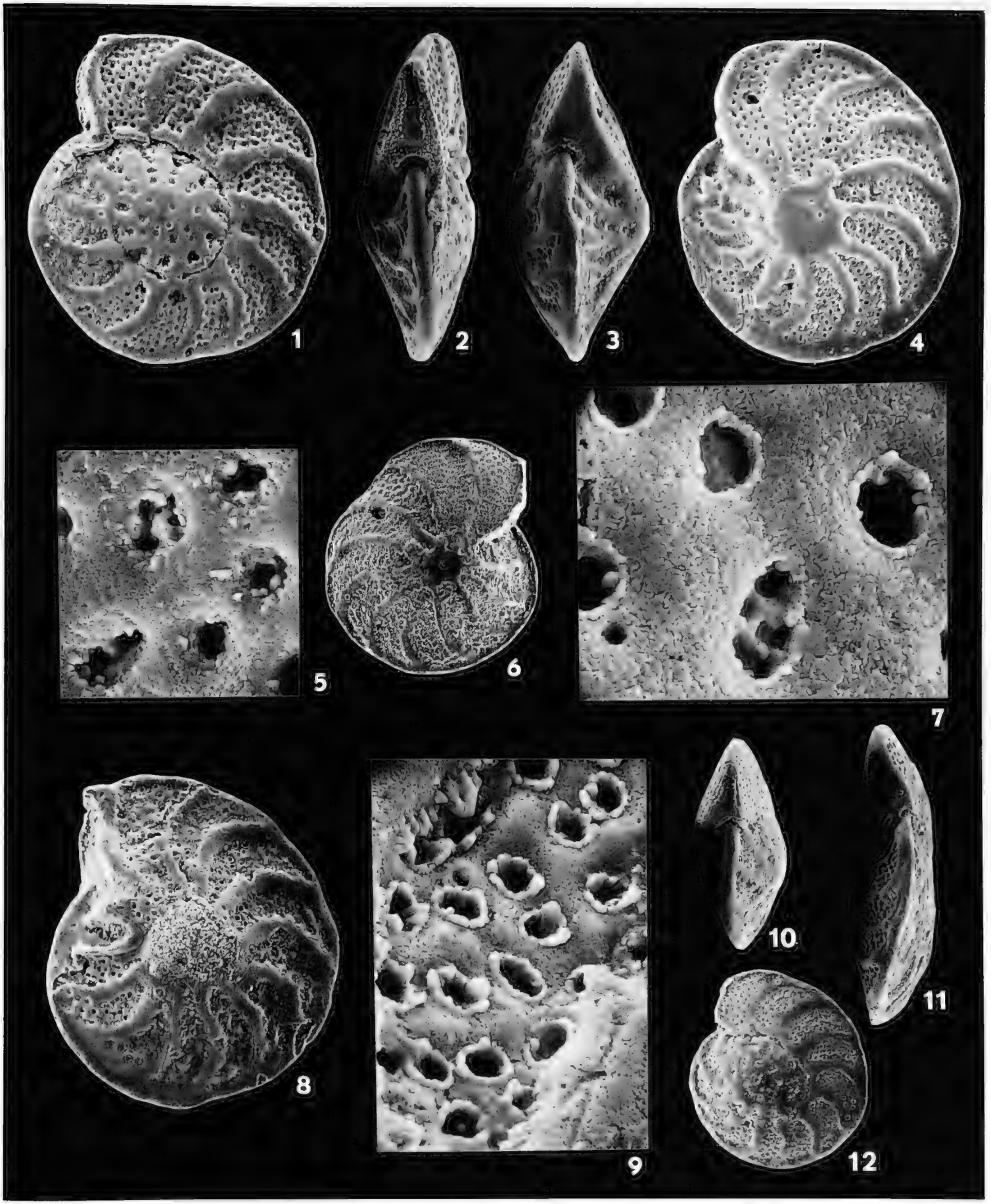
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## PLATE 15

*Svratkina croatanensis*, new species, Croatan and Yorktown Formations, North Carolina and Virginia

1, 2. Holotype, USNM 252546, USGS 25997: 1, spiral view; 2, edge view. Both × 225.
3, 4. Paratype, USNM 252547, USGS 25997: 3, edge view; 4, umbilical view. Both × 225.
5, 6. Paratype, USNM 252549, USGS 26001: 5, umbilical view; 6, edge view. Both × 195.
7, 8. Paratype, USNM 252550, USGS 26001: 7, umbilical view; 8, edge view. Both × 130.
9, 12. Paratype, USNM 252548, USGS 25997: 9, spiral view; 12, edge view. Both × 215.
10, 13. Paratype, USNM 252551, USGS 26001: 10, spiral view, × 170; 13, close-up of spiral surface, × 1430.
11. Paratype, USNM 252552, USGS 26001, spiral view, × 160.
14. Paratype, USNM 252553, USGS 26001, edge view, × 175.

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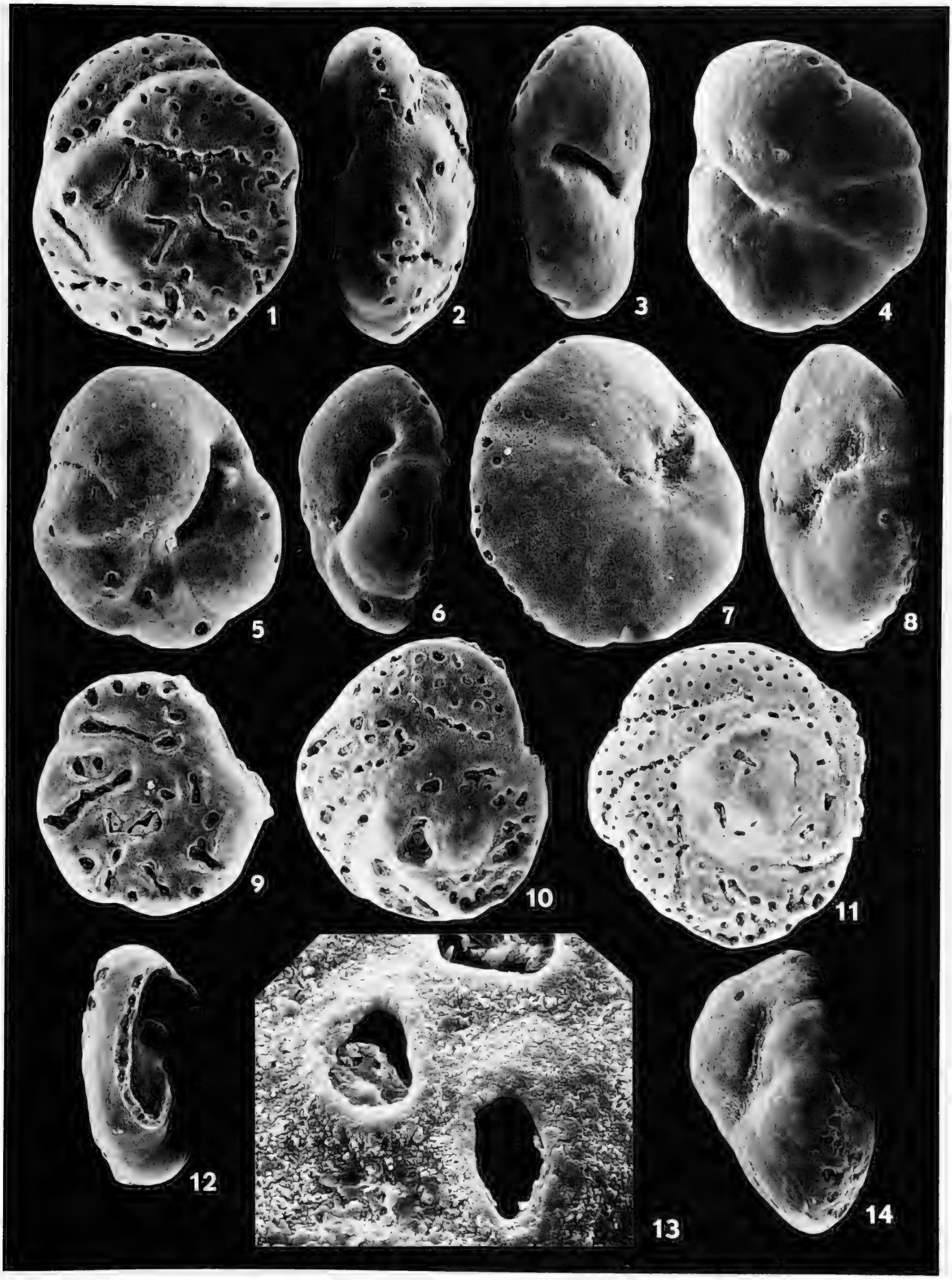
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## PLATE 16

1–3. *Spiroplectammina mississippiensis* (Cushman), Calvert Formation, Parker Creek, Maryland: 1, USNM 252595, USGS 25972, side view, × 88; 2, USNM 252596, USGS 25971, side view, × 88; 3, USNM 252596, USGS 25971, apertural view, × 88.

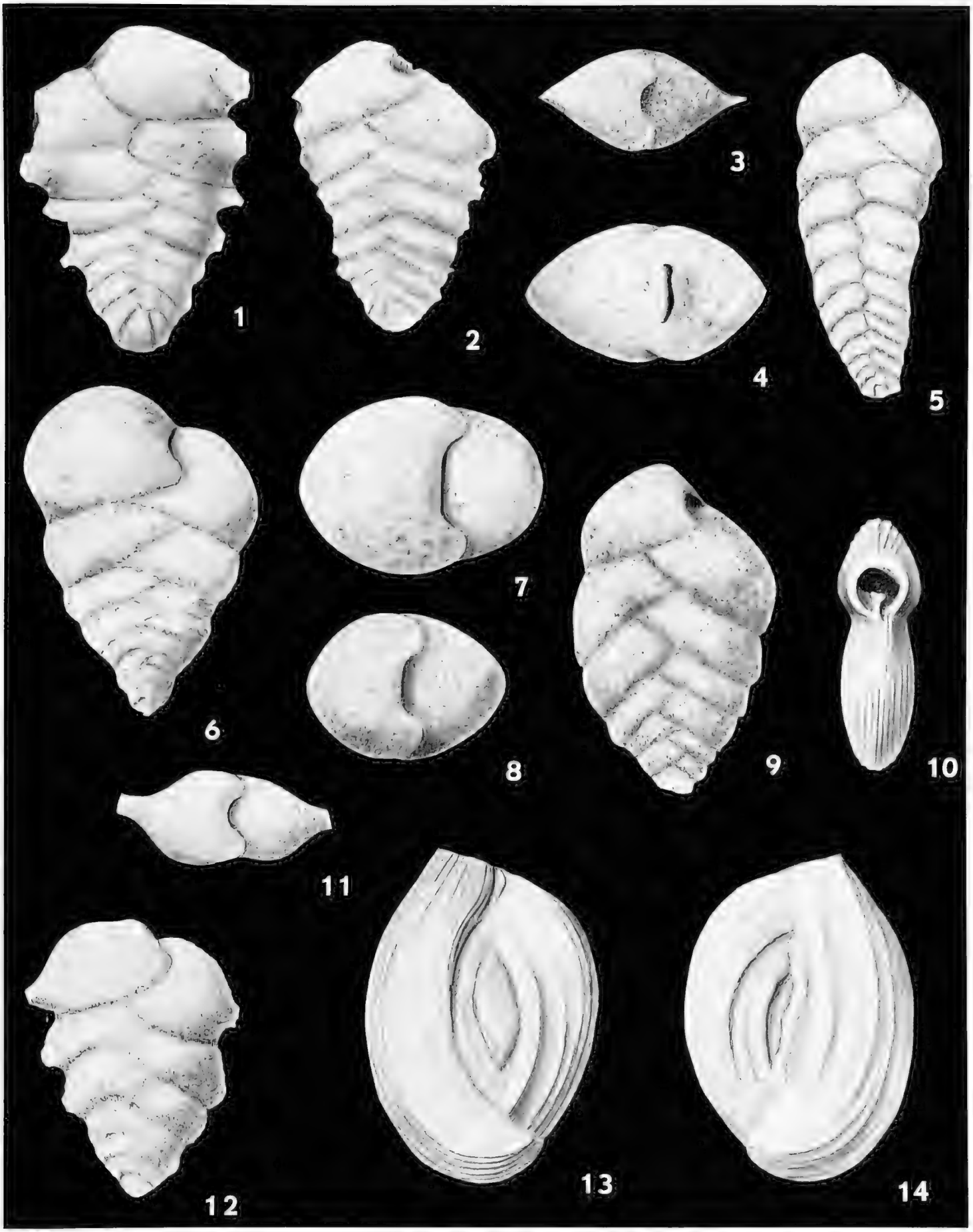
4, 5. *Spiroplectammina exilis* Dorsey, Choptank Formation, Nomini Cliffs, Virginia, USGS 25965: 4, USNM 252597, apertural view, × 112; 5, USNM 252598, side view, × 56.

6, 7. *Textularia ultima-inflata* Dorsey, Choptank Formation, Bartein's Landing, Maryland, USNM 252599, USGS 26019: 6, side view, × 66; 7, apertural view, × 66.

8, 9. *Textularia obliqua* Dorsey, St. Marys Formation, Chancellor Point, Maryland, USNM 252600, USGS 25957: 8, apertural view, × 56; 9, side view, × 56.

10, 13, 14. *Massilina marylandica* Cushman and Cahill, St. Marys Formation, Chancellor Point, Maryland, USNM 252601, USGS 25957: 10, apertural view, × 66; 13, side view, × 66; 14, side view, × 66.

11, 12. *Textularia mayori* Cushman, Yorktown Formation, Suffolk, Virginia, USNM 252602, USGS 25942: 11, apertural view, × 44; 12, side view, × 44.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## PLATE 17

1, 2, 6. *Quinqueloculina lamarckiana* d'Orbigny, Waccamaw Formation, near Town Creek, North Carolina, USNM 252603, USGS 25989: 1, side view; 2, side view; 6, apertural view. All × 88.

3, 4, 7. *Massilina glutinosa* Cushman and Cahill, Choptank Formation, Flag Pond, Maryland, USNM 252604, USGS 25962: 3, apertural view; 4, side view; 7, side view. All × 56.

5, 8. *Bolivina marginata multicostata* Cushman, Yorktown Formation, Yorktown, Virginia, USNM 252605, USGS 25933: 5, apertural view; 8, side view. Both × 112.

9, 10. *Sagrina pulchella primitiva* (Cushman), Waccamaw Formation, Walker's Bluff, North Carolina, USNM 252606, USGS 25926: 9, apertural view; 10, side view. Both × 140.

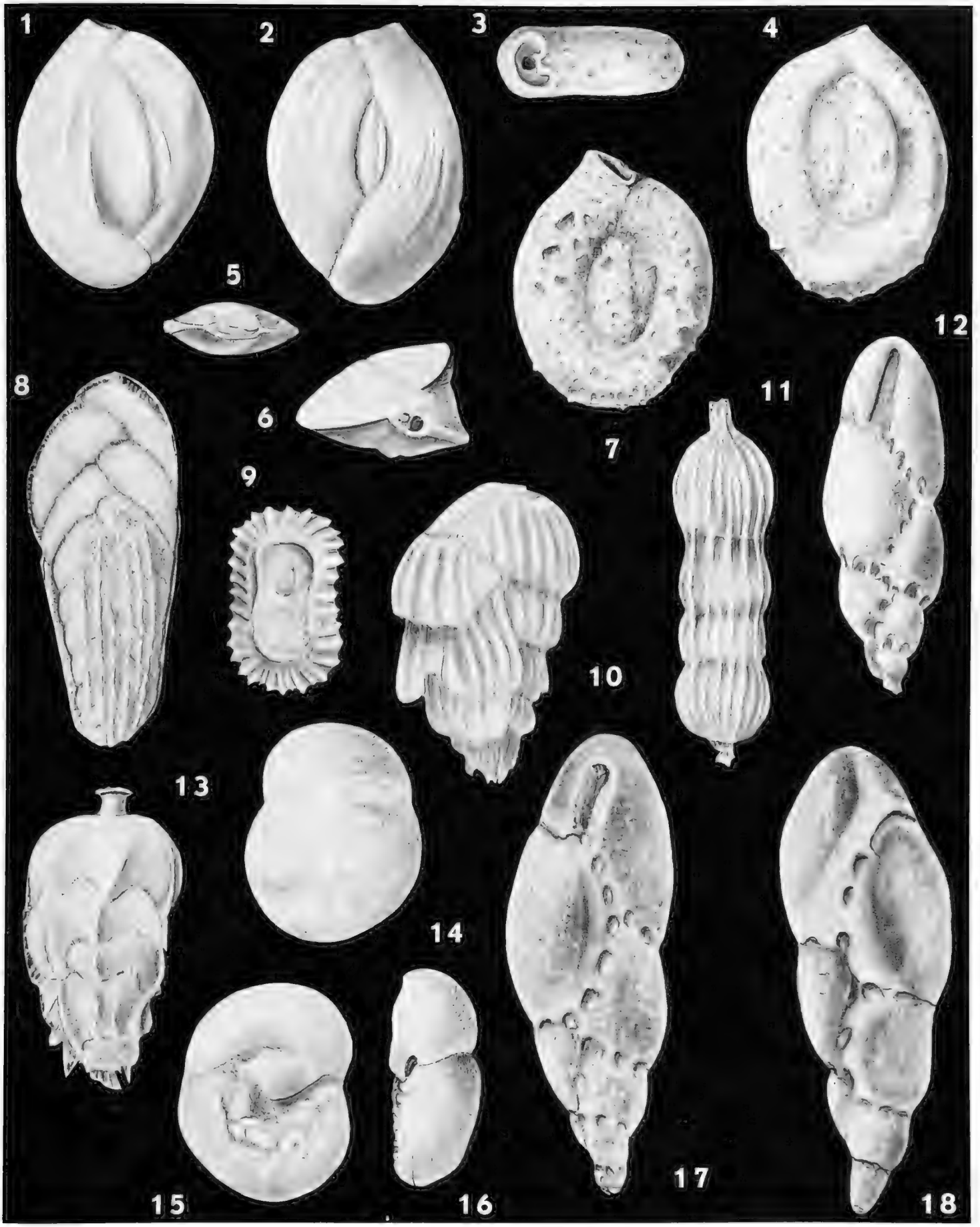
11. *Nodosaria catesbyi* d'Orbigny, Yorktown Formation, near Murfreesboro, North Carolina, USNM 252607, USGS 25948, side view, × 56.

12. *Virgulinella miocenica* (Cushman and Ponton), Choptank Formation, Nomini Cliffs, Virginia, USNM 252608, USGS 25965, side view, × 88.

13. *Siphogenerina lamellata* Cushman, Calvert Formation, Plum Point, Maryland, USNM 252610, USGS 25982, side view, × 148.

14–16. *Rosalina cavernata* (Dorsey), Calvert Formation, Plum Point, Maryland, USNM 252611, USGS 25977: 14, spiral view; 15, umbilical view; 16, end view. All × 88.

17, 18. *Virgulinella miocenica* (Cushman and ponton), St. Marys Formation, Windmill Point, Maryland, USNM 252609, USGS 25983: 17, front view; 18 back view. Both × 112.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## PLATE 18

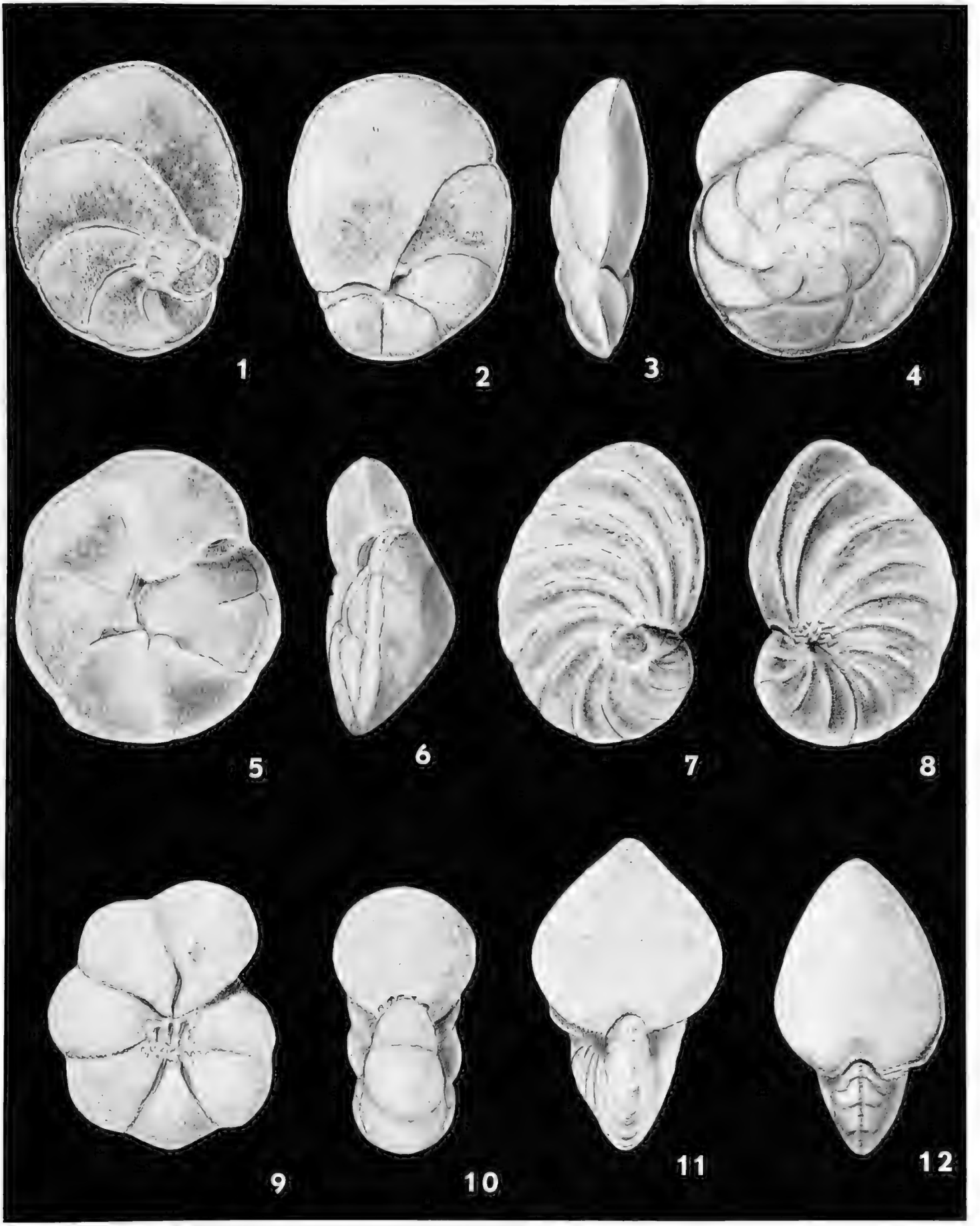
1–3. *Cancris sagra* (d'Orbigny), Yorktown Formation, Suffolk, Virginia, USNM 252612, USGS 25941: 1, spiral view; 2, umbilical view; 3, edge view. All × 88.

4–6. *Rotorbinella bassleri* (Cushman and Cahill), Calvert Formation, Governors Run, Maryland, USNM 252613, USGS 25969: 4, spiral view; 5, umbilical view; 6, edge view. All × 112.

7, 8, 12. *Florilus chesapeakensis*, new species, St. Marys Formation, Windmill Point, Maryland, paratypes, USNM 25266, USGS 25983: 7, spiral view; 8, umbilical view; 12, apertural view. All × 93.

9, 10. *Nonion marylandicum* Dorsey, Choptank Formation, Flag Pond, Maryland, USNM 252614, USGS 25960: 9, side view; 10, apertural view. Both × 112.

11. *Florilus chesapeakensis*, new species, Calvert Formation, Governors Run, Maryland, paratype, USNM 252567, USGS 25969, apertural view, × 88.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## PLATE 19

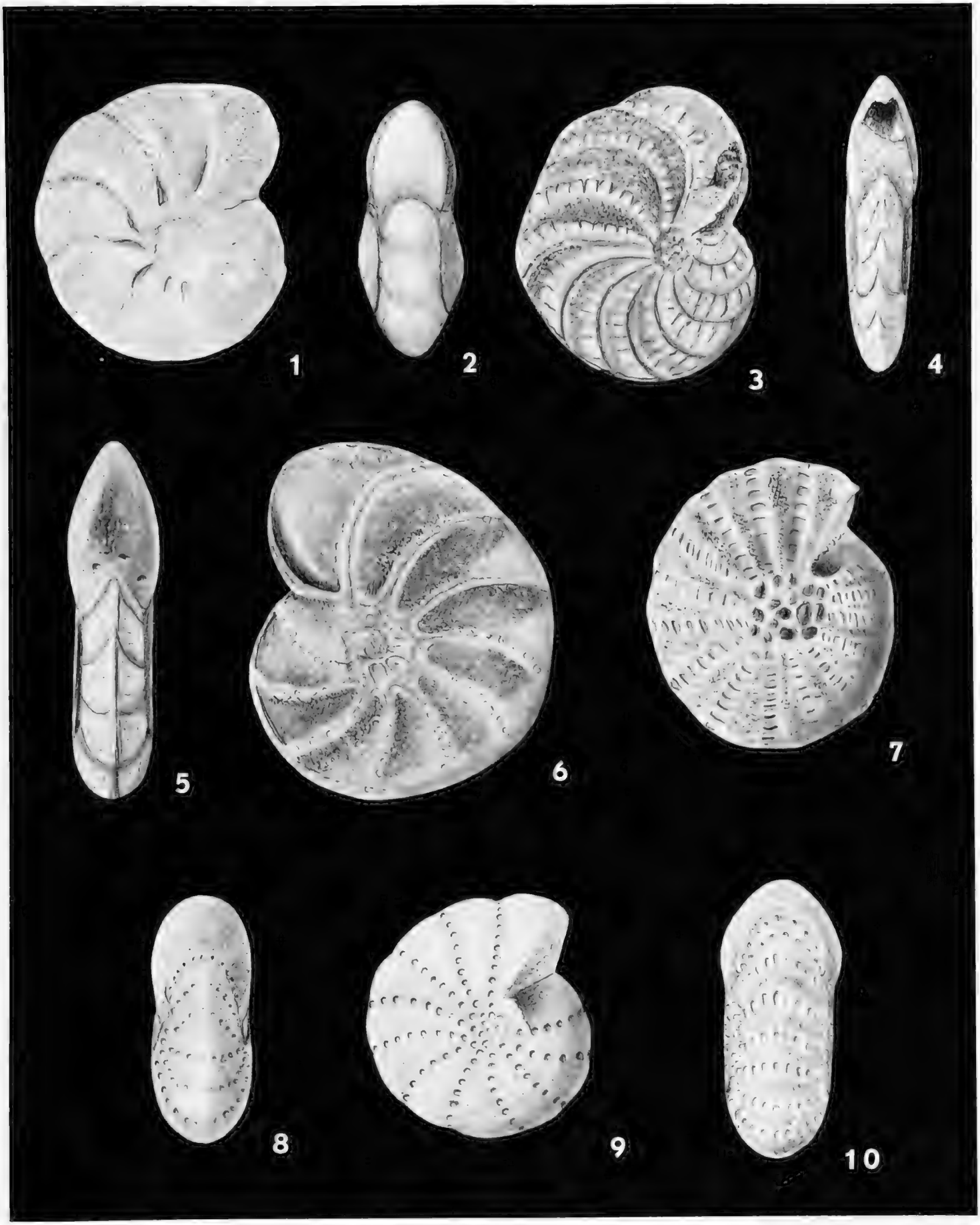
1, 2. *Nonion calvertensis*, new species, Calvert Formation, Randle Cliffs, Maryland, paratype, USNM 252558, USGS 25980: 1, side view; 2, apertural view. Both × 194.

3, 4. *Elphidium neocrespinae*, new species, Yorktown Formation, Black Rock Landing, Bertie County, North Carolina, paratype, USNM 252570, USGS 25930: 3, side view; 4, apertural view. Both × 88.

5, 6. *Elphidium compressulum* Copeland, Duplin Formation, near Kenansville, North Carolina, USNM 252615, USGS 25924: 5, apertural view; 6, side view. Both × 112.

7, 10. *Elphidium gunteri* Cole, Yorktown Formation, Mt. Gould Landing, North Carolina, USNM 252616, USGS 25927: 7, side view; 10, apertural view. Both × 88.

8, 9. *Elphidium latispatium pontium,* new subspecies, St. Marys Formation, Little Cove Point, Maryland, paratype, USNM 252573, USGS 25950: 8, apertural view; 9, side view. Both × 88.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## PLATE 20

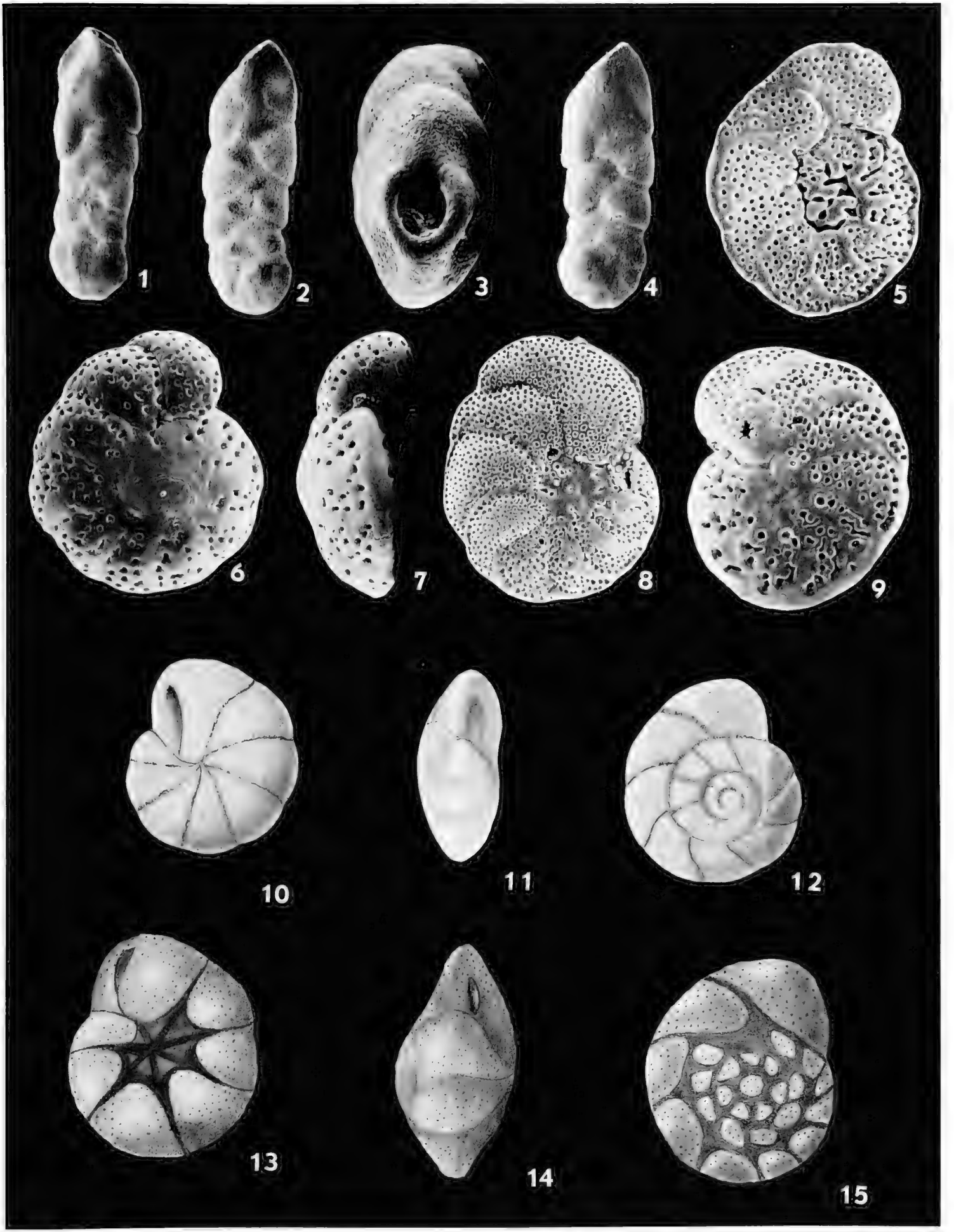
1–4. *Bolivinopsis fairhavenensis*, new species, Calvert Formation, Randle Cliffs, Maryland, USGS 25981: 1. paratype, USNM 252519, side view, × 300; 2, holotype, USNM 252518, side view, × 300; 3, holotype, USNM 252518, apertural view, × 660; 4, paratype, USNM 252520, side view, × 340.

5–9. *Cibicides croatanensis*, new species, Croatan Formation, Lee Creek Mine, North Carolina, USGS 25997: 5. Paratype, USNM 252536, spiral view, × 120; 6, paratype, USNM 252537, umbilical view, × 210; 7, paratype, USNM 252537, edge view, × 210; 8. paratype, USNM 252538, umbilical view, × 100; 9. paratype, USNM 252539, umbilical view, × 130.

10–12. *Epistominella danvillensis* (Howe and Wallace), Yorktown Formation, Morgart's Beach, Virginia, USNM 252617, USGS 25937: 10, umbilical view; 11, edge view; 12, spiral view. All × 194.

13–15. *Epistominella pungoensis*, new species, Pungo River Formation, Moores Bridge Well, Norfolk, Virginia, holotype, USNM 252521, USGS 26003: 13, umbilical view; 14, edge view; 15, spiral view. All × 200.

Micrographs reduced to 97½% for publication.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## PLATE 21

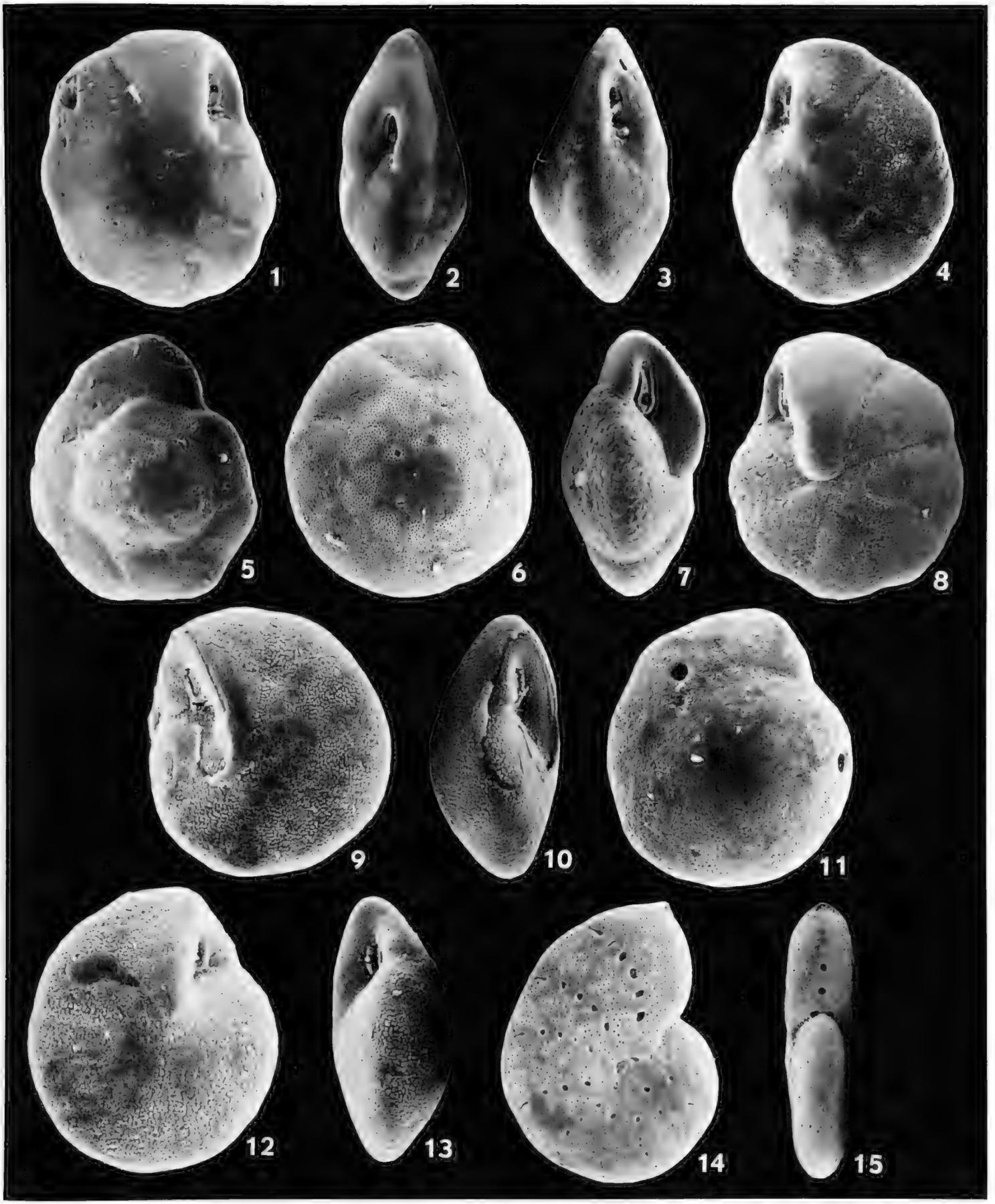
1–6. *Epistominella pungoensis*, new species, Pungo River Formation, Moores Bridge Well, Norfolk, Virginia, paratypes, USGS 26003: 1, USNM 252522, umbilical view, × 400; 2, USNM 252522, edge view, × 400; 3, USNM 252523, edge view, × 500; 4, USNM 252523, umbilical view, × 500; 5, USNM 252524, spiral view, × 300; 6, USNM 252525, spiral view, × 340.

7, 8. *Epistominella pontoni* (Cushman), Choctawhatchee Formation, Alice Creek, Florida, USNM 252618, USGS 25922: 7, edge view, × 300; 8, umbilical view, × 300.

9–13. *Epistominella danvillensis* (Howe and Wallace), Yorktown Formation, Lee Creek Mine, North Carolina, USGS 26010: 9, USNM 252619, umbilical view; 10, USNM 252619, edge view; 11, USNM 252620, spiral view; 12, USNM 252621, umbilical view; 13, USNM 252621, edge view. All × 500.

14, 15. *Elphidium compressulum* Copeland, Duplin Formation, Natural Well, North Carolina, USNM 252622, USGS 25923: 14, side view, × 200; 15, apertural view, × 200.

Micrographs reduced to 94% for publication.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## PLATE 22

1, 2. *Nonion advenum pustulosum*, new subspecies, Silverdale beds of Vokes (1967), near Long Point, North Carolina, holotype, USNM 252561, USGS 22294: 1, side view; 2, apertural view. Both × 160.

3, 11–12. *Elphidium latispatium latispatium* Poag, Chickasawhay Formation, Choctaw Bluff, Alabama, USGS 25921: 3, USNM 252623, apertural view; 11, USNM 252624, side view; 12, USNM 252623, side view. All × 200.

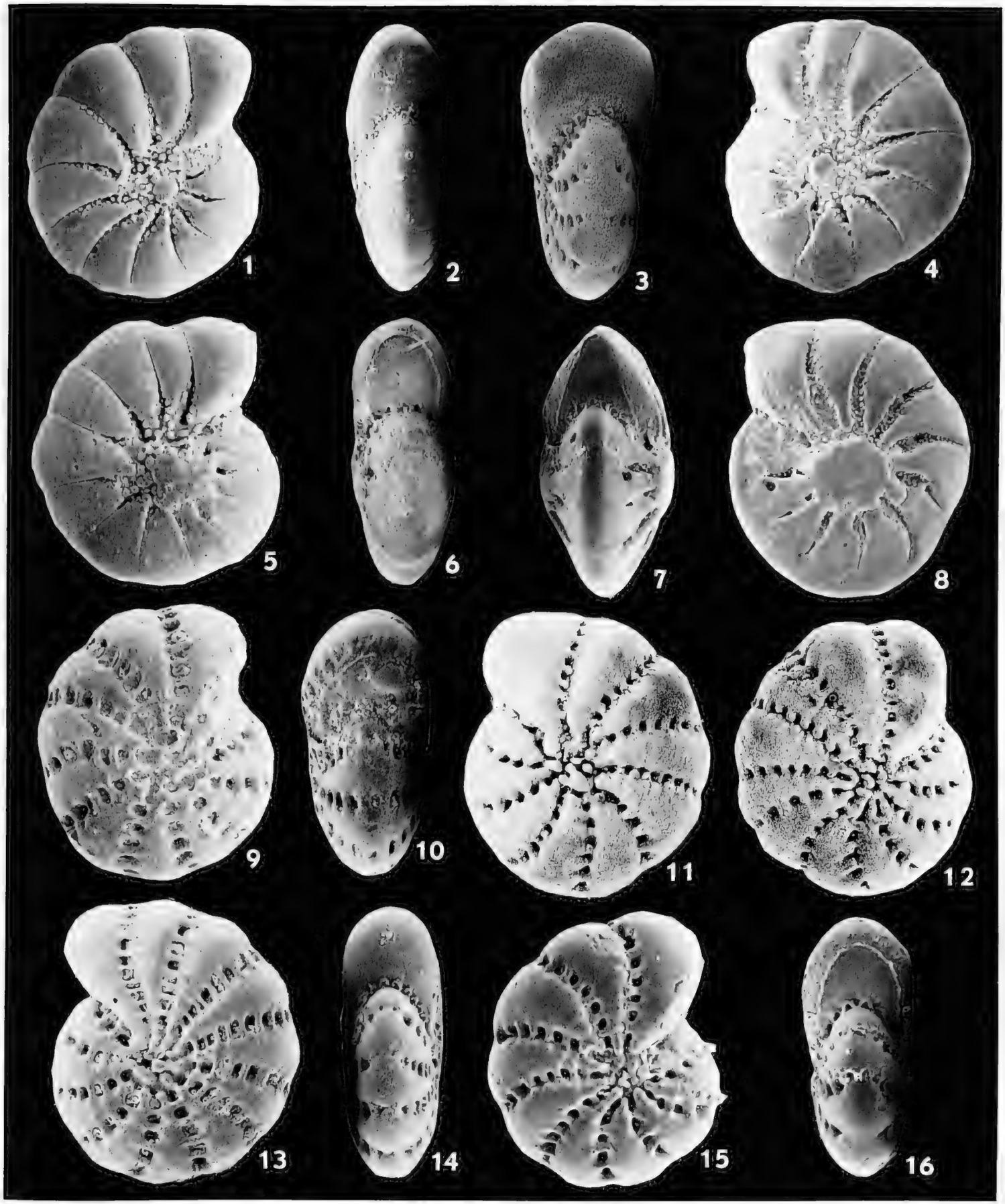
4–6. *Nonion advenum pustulosum*, new subspecies, Silverdale beds of Vokes (1967), near Long Point, North Carolina, paratypes, USGS 22294: 4, USNM 252562, side view, × 160; 5, USNM 252563, side view, × 180; 6, USNM 252563, apertural view, × 180.

7, 8. *Nonion advenum advenum* (Cushman), Chickasawhay Formation, Choctaw Bluff, Alabama, USNM 252626, USGS 25921: 7, apertural view; 8, side view. Both × 200.

9, 10, 13, 14. *Elphidium latispatium pontium*, new subspecies, Silverdale beds of Vokes (1967), near Long Point, North Carolina, paratypes, USGS 22294: 9, USNM 252574, side view, × 200; 10, USNM 252574, apertural view, × 200; 13, USNM 252575, side view, × 160; 14, USNM 252575, apertural view, × 160.

15, 16. *Elphidium latispatium latispatium* Poag, Paynes Hammock Formation, near Waynesboro, Mississippi, USNM 252625, USGS 25966: 15, side view; 16, apertural view. Both × 240.

Micrographs reduced to 93% for publication.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# Planktonic Foraminifera and Biostratigraphy of the Yorktown Formation, Lee Creek Mine

*Scott W. Snyder, Lucy L. Mauger, and W.H. Akers*

ABSTRACT

The open-pit phosphate mine of Texasgulf Inc. at Lee Creek provides the most nearly complete section of the Yorktown Formation in North Carolina. The Yorktown exposure at this locality has yielded a rich and diverse vertebrate fauna. However, the biostratigraphic position of this important exposure has been difficult to determine because previous studies of planktonic foraminifera have yielded too few species to provide a basis for precise interpretation. During this study 29 species and subspecies of planktonic foraminifera were identified from 42 samples taken at vertical intervals of 35 cm through a 15 m section of the Yorktown Formation. Concurrent portions of the range zones of eight taxa indicate an age of late early to early late Pliocene (from just below the base of Blow's zone N19 to the middle of his zone N20).

## Introduction

The Yorktown Formation is the youngest of the four formations that compose the Chesapeake group. This group crops out in a broad belt across much of the Coastal Plain of Maryland, Virginia, and North Carolina. The oldest formation of the Chesapeake group, the Calvert, and its equivalents were deposited during a marine transgression that covered most of the middle Atlantic Coastal Plain, except for southeastern North Carolina. During two subsequent regressive stages the Choptank Formation and later the St. Marys Formation were deposited. These three formations are thickest in Maryland and in a small area of northeastern Virginia. Slightly before or during early Yorktown time tectonic movement resulted in a southward shift in the locus of deposition. Yorktown seas covered parts of southern Virginia and most of northeastern North Carolina (Gibson, 1962, 1967, 1970).

Surface exposures of the Chesapeake group are scarce because of Pleistocene cover, low regional relief, and the unconsolidated or weakly lithified nature of the formations that comprise it. Natural exposures occur along river and stream banks. Isolated exposures that have been interpreted as the Yorktown Formation are found from the Rappahannock River in Virginia to the Neuse River in North Carolina (Bailey, 1973:2, fig. 1).

Although some information on the nature of Yorktown sediments in the subsurface has been gathered from well cuttings, thick, richly fossiliferous surface exposures were not available south of the Meherrin-Chowan area of northeastern North Carolina until 1965, when Texas Gulf Sulphur Company (now Texasgulf Inc.) began open-pit mining at the mouth of Lee Creek on the south shore of the Pamlico River (Figure 1). Mining operations have exposed a remarkable Neogene fossil locality. The Yorktown Formation at this locality has yielded an exceptionally rich and diverse vertebrate fauna (C. Ray, pers.

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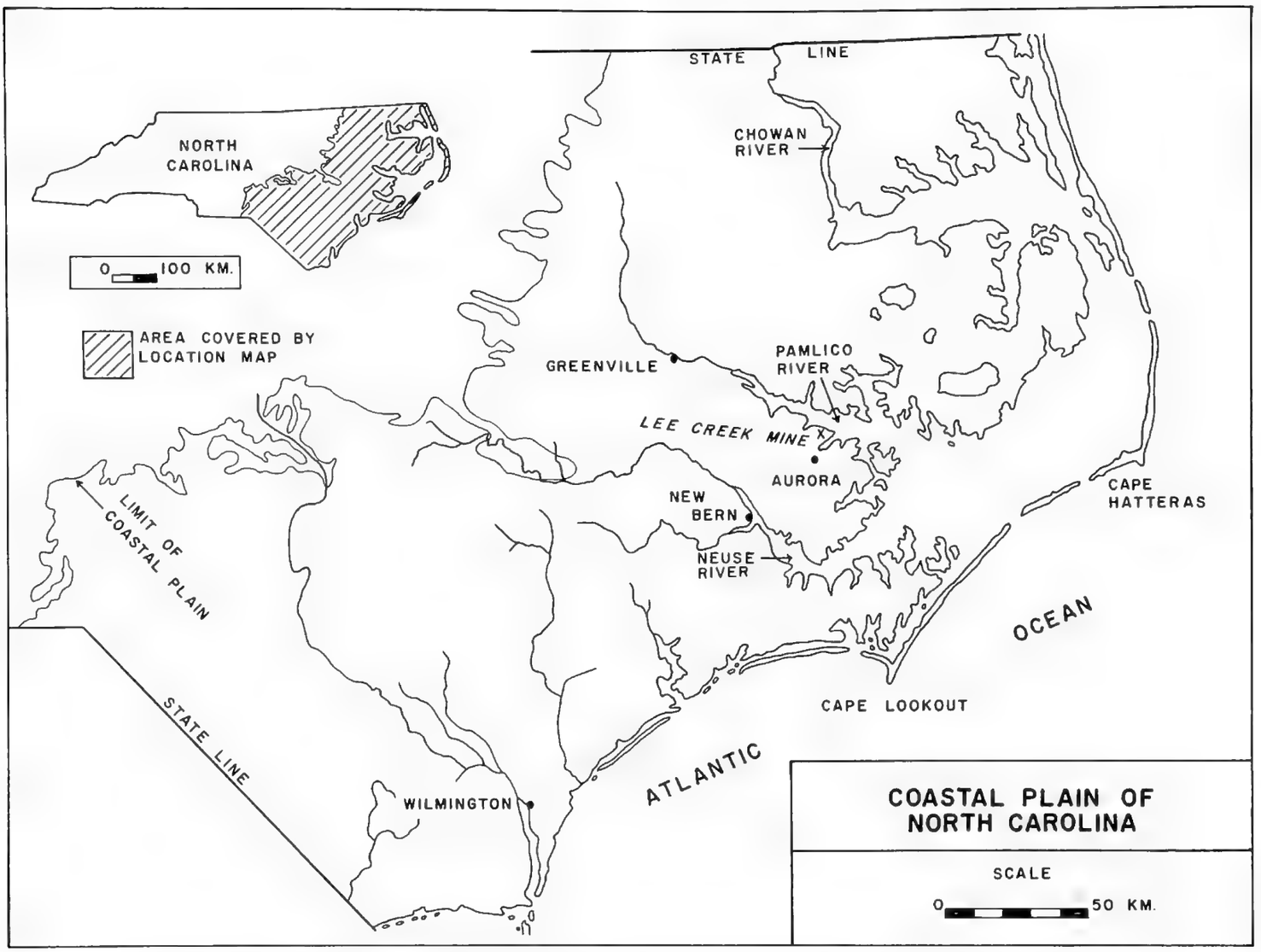


FIGURE 1.—Map of the North Carolina Coastal Plain showing localities mentioned in text.

comm.), knowledge of which will be enhanced by a precise biostratigraphic interpretation.

ACKNOWLEDGMENTS.—Permission to sample the ore cut was obtained largely through the efforts of Ralph Chamness, geologist for Texasgulf Inc. Thomas Gibson of the U.S. Geological Survey and Clayton Ray of the Smithsonian Institution provided helpful suggestions and criticisms in their review of the manuscript.

## Previous Work

The earliest widely accepted biostratigraphic subdivision of the Yorktown Formation was that of Mansfield (1943), in which he proposed a zonation based on the mollusks. The formation was divided into the following two biostratigraphic units: a lower zone 1 (*Placopecten clintonius*) and an upper zone 2 (*Turritella alticostata*). Despite criticism that some of his correlations involving certain units in zone 2 are not justified, Mansfield's two-zone scheme has provided a workable zonation for the Yorktown Formation in Virginia (Bailey, 1973; Hazel, 1971). It has also been used frequently in North Carolina.

Although useful on a regional scale within the Atlantic Coastal Plain, the Yorktown molluscan fauna has proven inadequate for intercontinental correlation (Mongin, 1959:285, 287, 333). Early investigations of the Yorktown microfauna failed

to provide more accurate biostratigraphic interpretations. These studies, which dealt primarily with benthic Foraminifera, were summarized by McLean (1956).

The first published study of the exposure at Lee Creek was that of Gibson (1967). The planktonic foraminiferal assemblage from the lower part of the Yorktown section, although sparse, was interpreted as middle late Miocene in age, while the age of the upper part of the formation remained questionable. During the early 1970s several workers suggested that the age of the Yorktown Formation, traditionally considered to be Miocene, might be re-interpreted as younger. Hazel (1971) divided the formation into three ostracode assemblage zones and concluded that Yorktown sediments exposed along the Chowan River near Mount Gould, North Carolina, are Pliocene. Gibson (1971) emphasized the need to find adequate planktonic assemblages in order to determine whether or not upper Yorktown units range into the Pliocene. Akers (1972) examined planktonic Foraminifera from several Yorktown localities, including Lee Creek, and concluded that at least part of the formation (at Rice's Pit, Virginia) is early to early middle Pliocene. He found the assemblages at Lee Creek to be too impoverished to serve as a basis for exact correlation. Akers and Koeppel (1973) analyzed the calcareous nannoplankton of the Yorktown section at Lee Creek as part of a study concerning Neogene formations of the Atlantic Coastal Plain. The flora recovered from the Lee Creek exposure includes *Gephyrocapsa caribbeanica*, a form then considered to indicate an early Pleistocene age. However, this species appears to be indigenous to several Pliocene formations, and they concluded that an age of middle Pliocene for the Yorktown is consistent with the total faunal and floral evidence. Gibson (p. 363, herein) has re-examined planktonic foraminiferal assemblages from Yorktown exposures as part of a study on key Foraminifera from sediments of the middle Atlantic Coastal Plain. He interpreted the age of the Yorktown Formation as ranging from early Pliocene through late Pliocene. However, he also applies the term "Yorktown" to sediments that are younger than those traditionally identified as part of this formation. Gibson's "uppermost Yorktown," exposed along the Chowan River in northeastern North Carolina, contains species indicative of an early Pleistocene age. Blackwelder (1980) removed these strata from the Yorktown Formation, designating them the Chowan River Formation.

## Objectives

Although planktonic Foraminifera from the Yorktown Formation in North Carolina have been analyzed before, a detailed study of the assemblages at the Lee Creek exposure has not previously been undertaken. Akers (1972) recorded only seven species, which included too few marker species to support a precise biostratigraphic interpretation. Gibson (p. 355, herein) recorded 16 species from 8 localities in North Carolina and Virginia. However, his four samples from Lee Creek yielded only half of that total.

This study is based on a large number of bulk samples taken at short stratigraphic intervals. The primary objective is to provide a more accurate biostratigraphic interpretation of this important Yorktown exposure than has previously been possible.

## Procedures

Forty-two samples weighing from 1 to 2.5 kg each were collected from the Yorktown Formation at vertical intervals of 35 cm (Figure 2). In order to minimize the possibility of contamination, several centimeters of sediment were removed from the wall prior to collecting each sample. Each sample represents a stratigraphic thickness of 3 to 4 cm.

Samples were placed in distilled water for several days and then sieved through a No. 14 (1.41 mm) and a No. 230 (0.063 mm) U.S. Standard Sieve. The sample fraction trapped on the latter sieve was boiled in a Calgon-distilled water solution and washed to disperse clays.

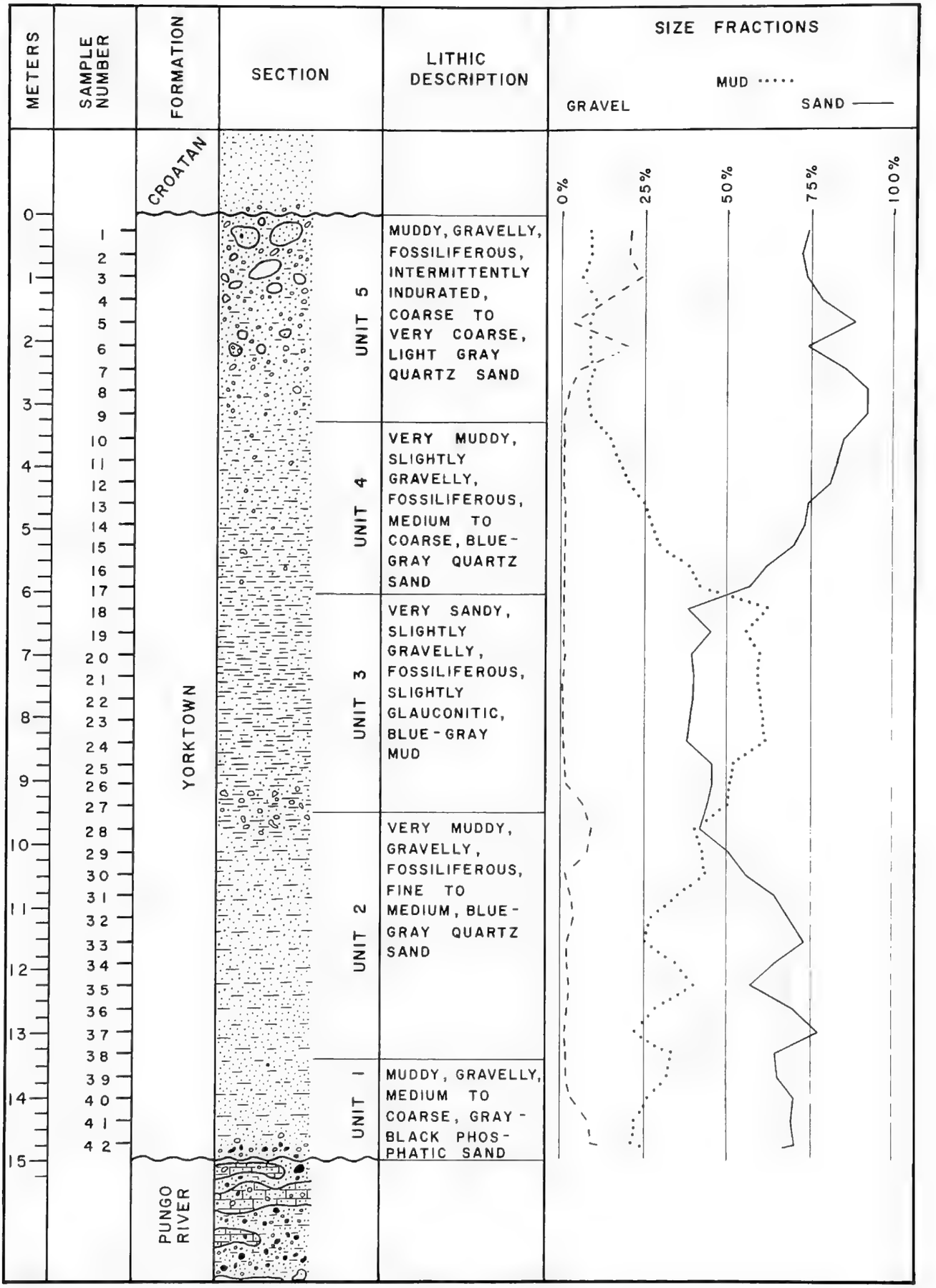


FIGURE 2.—Measured 15-meter section of the Yorktown Formation in the Lee Creek Mine.

Microfossils were then separated by flotation on a solution of sudsing detergent and distilled water. The soap float residue, which consisted of very fine to fine sand and microfossils, was boiled in 0.5 liter of distilled water to which a few drops of Quaternary "O" had been added. (Quaternary "O" is a highly active, low sudsing detergent that successfully disaggregates clays that persist throughout the washing process.) The clean residue from each sample was then dried and floated on carbon tetrachloride to further concentrate the microfossils. Spot checks of sample material that did not float revealed that the separation was clean and dependable. The entire microfossil concentrate from each sample was carefully examined to ensure that rare species would not be overlooked.

## Lithologic Description

Weight percentages of the gravel, sand, and mud (silt + clay) fractions were determined for each sample and are plotted graphically in Figure 2. The Yorktown Formation at Lee Creek is generally a very muddy quartz sand. With the exception of the uppermost part of the section, the entire formation contains more than 15 percent mud. Ten samples from the middle part of the formation (Figure 2: unit 3) are more than 50 percent mud. The remainder of the section is sandier. Twenty-one of the samples contain at least 70 percent sand. The upper 5.3 m has the highest sand content; two samples in this upper part are more than 90 percent sand.

Gravel-sized pieces of shell material and cemented sediment comprise less than 3 percent of most samples. However, the gravel-sized fraction in parts of the "boulder bed" (Figure 2: unit 5) exceeds 20 percent. These "boulders" are not detrital; rather they are composed of calcite-cemented clumps of sediment and abundant shell hash, primarily bivalve and barnacle. The upper contact of the Yorktown Formation has generally been placed at the base of this "boulder bed," which also has less mud and more sand than any of the underlying units. Groundwater steadily seeps from the quarry wall along the irregular lower boundary of this unit and stains the exposed surface of underlying sediments, thus creating a rather striking "contact." However, the upper surface of this unit is also irregular and the entire unit is absent in places. The unit is best developed where the upper surface is at higher elevations, less conspicuous and thinner where it begins to dip, and absent in areas between local highs. Rather than being a primary depositional unit, the "boulder bed" may represent a zone of alteration developed on and immediately below a paleosurface, the exact nature of which is unknown. If so, the unconformity lies along its upper surface. More detailed work will be necessary to determine the origin of the unit. For the purposes of this study, however, it has been included as part of the Yorktown Formation. Including the "boulder bed," the total thickness of the Yorktown exposure is 15 m.

The only part of the middle Yorktown section that contains a large amount of gravel-sized material (9 percent) is an extensively leached, partially indurated zone that contains abundant molds of turritellid gastropods and cemented clumps of sediment. A zone at the base of the formation contains gravel-sized material in the form of shell hash and phosphate granules, pebbles, and cobbles.

On the basis of sedimentological data, five lithologic units have been defined within the Yorktown section at Lee Creek (Figure 2). These range from a muddy phosphatic quartz sand (unit 1) at the base; through a very sandy blue-gray mud (unit 3) in the middle; to a light gray quartz sand with much gravel-sized material (unit 5) at the top. All units contain Foraminifera.

## Results

P/P + B Ratios.—In order to determine the abundance of planktonic vs benthic Foraminifera within each sample, specimens of both were picked from a tray divided into a number of systematically arranged segments. A random

sampling was obtained by picking specimens from predetermined segments of the tray until 300 to 400 benthic Foraminifera had been recovered.

The P/P + B ratio values of each sample are plotted in Figure 3. Values range from nearly zero to a maximum of 0.65. The general pattern of these values supports evidence based on benthic Foraminifera that indicates marine transgression through the lower part of the section, a near stillstand in sea level through the middle part, followed by regression in the upper part (Mauger, 1979). Large-scale fluctuations in ratios through the middle part of the section reflect diagenetic alteration that preferentially destroyed planktonic species. For example, low values for samples 26–28 are related to a strongly leached zone characterized by calcite-cemented sediment fragments (Figure 2).

The number of planktonic species present in individual samples is closely related to the P/P + B ratio. The number of species ranges from 1 to 22. Fifty percent of the samples yielded 10 or fewer species, which may explain why previous studies, based on a smaller number of samples, recorded so few species from Lee Creek.

Planktonic Fauna.—Twenty-nine species and subspecies of planktonic Foraminifera have been identified from the Yorktown exposure at Lee Creek. The stratigraphic occurrence and relative abundance of each is shown in Figure 4. Values of relative abundance, computed as a percentage of the total planktonic foraminiferal assemblage, fall into three categories: (1) rare, less than 1 percent; (2) few to common, 1 to 10 percent; (3) very abundant, greater than 70 percent. These categories are used because actual percentages, particularly for species with low relative abundance, have been strongly altered by solution. No species comprises more than 10 but less than 70 percent of the fauna in any of the samples.

The dominant species is *Globigerina bulloides bulloides*, which comprises 70 to 100 percent of each sample. Seven other species account for more than 1 percent of the assemblage in one or more samples. Thus, 21 of 29 species and subspecies are rare and occur only sporadically within the section.

Gibson (p. 355, herein) states that the Yorktown foraminiferal assemblage is indicative of cool water. In modern faunas *G. bulloides* attains maximum relative abundances in the cool-temperate faunal province (Bé, 1959:87, 88, figs. 25, 26; Boltovskoy, 1966:9, graphs 1–3, 1969:243, fig. 2; Cifelli and Smith, 1970:20). Its dominance in our samples, especially in those that are well preserved, supports Gibson's interpretation. Tropical and subtropical species, many of which are the most useful biostratigraphically, would logically be rare in such waters. However, the dominance of *G. bulloides bulloides* may be secondarily enhanced in some samples (those in which its relative abundance approaches 100 percent). These samples occur only in leached zones where solution has altered the fauna. An experimentally derived hierarchy of resistance to solution includes many of the modern planktonic foraminiferal species (Jenkins and Orr, 1972). Among those species from the Yorktown Formation for which information is available, four are less resistant, two are slightly more resistant, and one is substantially more resistant to solution than is *G. bulloides*. We are unaware of any such data for the extinct species encountered during this study.

Although *G. bulloides* is only intermediate in resistance to solution among modern planktonic foraminifera, its initial abundance in the Yorktown fauna may explain why it remains where other species have been destroyed. Indeed, specimens of *G. bulloides bulloides* are poorly preserved and often heavily encrusted with secondary calcite in these zones of alteration. Rarer species, if initially present, may not have survived the destructive processes. Initial abundance plays an important role in determining whether a species escapes a variety of potentially destructive processes (Snyder, 1978).

Biostratigraphic Interpretation.—Numerous studies of planktonic foraminiferal assemblages from Cenozoic sediments in various parts of the world show that the species composition of such faunas is not uniform. According to Bolli

| SAMPLE | Number of Planktonic Foraminifera | Number of Benthic Foraminifera |
|---|---|---|
| 1 | 5 | 333 |
| 2 | 20 | 502 |
| 3 | 45 | 350 |
| 4 | 18 | 239 |
| 5 | 32 | 357 |
| 6 | 29 | 354 |
| 7 | 50 | 330 |
| 8 | 16 | 352 |
| 9 | 26 | 400 |
| 10 | 39 | 386 |
| 11 | 41 | 351 |
| 12 | 42 | 381 |
| 13 | 50 | 346 |
| 14 | 55 | 351 |
| 15 | 77 | 396 |
| 16 | 164 | 362 |
| 17 | 152 | 312 |
| 18 | 180 | 373 |
| 19 | 480 | 307 |
| 20 | 266 | 296 |
| 21 | 119 | 298 |
| 22 | 233 | 325 |
| 23 | 642 | 318 |
| 24 | 174 | 386 |
| 25 | 306 | 317 |
| 26 | 10 | 333 |
| 27 | 19 | 325 |
| 28 | 12 | 323 |
| 29 | 99 | 310 |
| 30 | 324 | 362 |
| 31 | 54 | 350 |
| 32 | 281 | 349 |
| 33 | 32 | 314 |
| 34 | 116 | 380 |
| 35 | 244 | 360 |
| 36 | 98 | 377 |
| 37 | 80 | 331 |
| 38 | 15 | 400 |
| 39 | 17 | 355 |
| 40 | 37 | 359 |
| 41 | 16 | 330 |
| 42 | 6 | 358 |

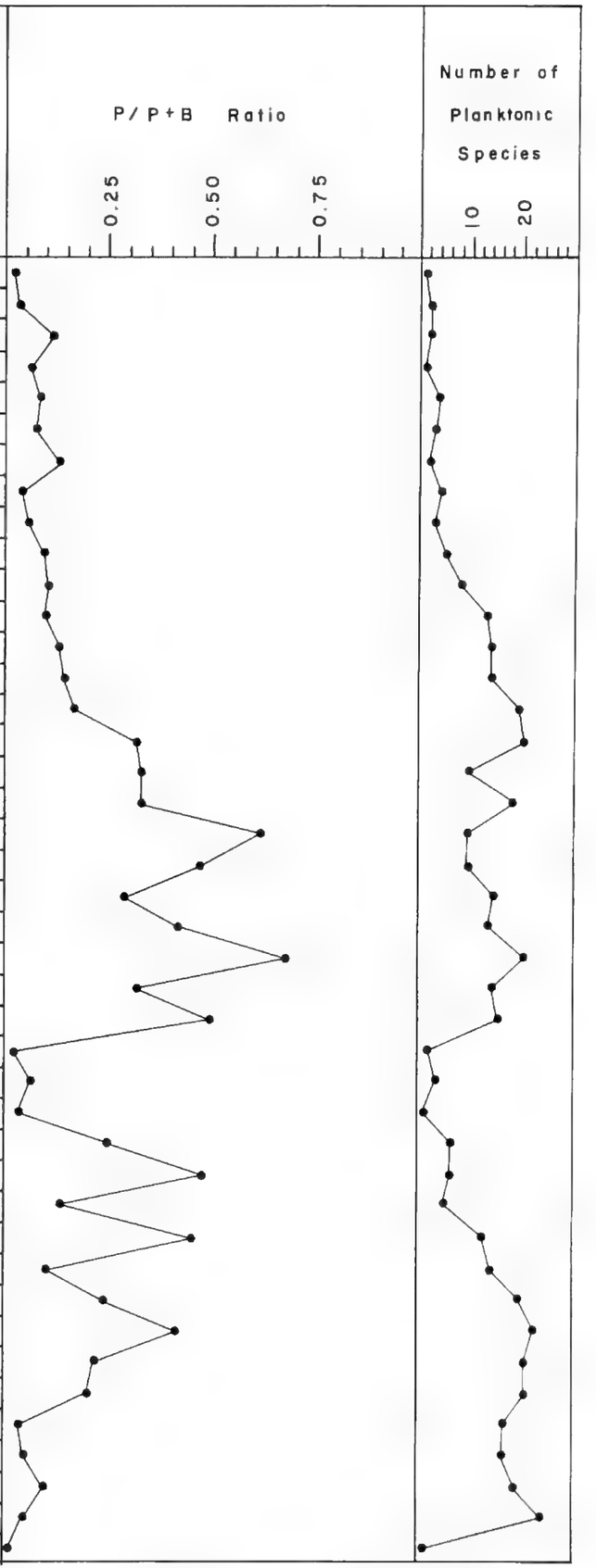


FIGURE 3.—Abundance of planktonic and benthic Foraminifera in the measured section of the Yorktown Formation, based on counts of individuals from subsamples drawn randomly from each of the 42 samples, expressed in terms of the ratio of planktonic (P) to planktonic plus benthic (P + B) specimens. The number of planktonic species represented in each sample is indicated in the righthand column.

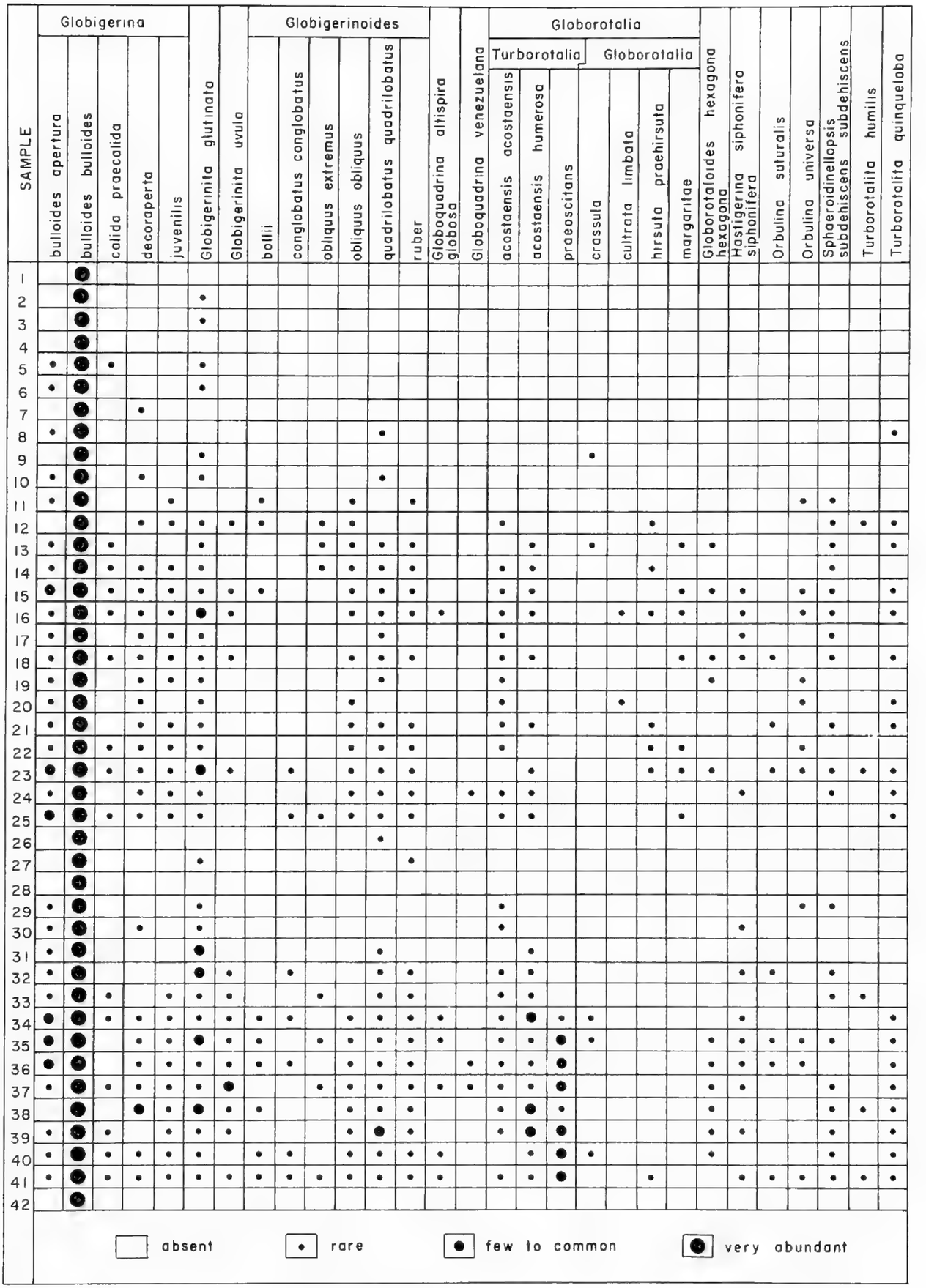


FIGURE 4.—Occurrence of planktonic foraminiferal species in samples from the Yorktown section at Lee Creek.

and Krasheninnikov (1977:438, 444), the primary factor in controlling species distributions is water temperature, which produces a latitudinal restriction of species that has intensified throughout the Cenozoic. Workers dealing with Neogene sediments, in which the effects of this provincialism are most pronounced, have proposed zonal schemes to supplement those originally based on tropical faunas. Examples include the zonations of Berggren (1971) for the North Atlantic and of Poore and Berggren (1975) for temperate regions of the northeastern Atlantic. However, the faunas from temperate (midlatitude) zones yield less biostratigraphic resolution than do those from tropical zones (Berggren, 1978:342).

Because maximum resolution and accuracy are the objects of any biostratigraphic study, it is desirable to correlate, if possible, with one of the zonal schemes based on tropical assemblages. Blow (1969) divided the Neogene into 23 planktonic foraminiferal zones. His zonal scheme has been used as a standard for correlation by numerous workers. The somewhat more detailed zonation of the Pliocene by Berggren (1973) is also based on tropical assemblages.

Although the planktonic foraminiferal assemblage from the Yorktown Formation at Lee Creek is numerically dominated by cool-temperate and cosmopolitan species, it contains a sufficient number of tropical species to permit correlation with the zones of Blow and Berggren. The assemblages from the Lee Creek exposure lend themselves to comparison with Berggren's zonation because many of the species present are used in his zonal boundary definitions. In contrast, virtually none of the species used to define Blow's zonal boundaries are present at Lee Creek. However, the first appearance of several species and the extinction level of others can be used to correlate with either of these zonal schemes. Blow's zonation has been emphasized in this report because it is better known, but correlation with both preceding zonal schemes is discussed below.

Anomalies in stratigraphic and paleogeographic species distributions, for example the temporary provincial predominance of certain taxa in Pliocene sediments of the Caribbean, limit the application of any established zonal scheme (Bolli and Krasheninnikov, 1977). For this reason, species stratigraphic ranges from Blow (1969) have been modified when more recent information from geographic localities closer to Lee Creek is available (Figure 5). This approach is the only way to compensate for irregularities in faunal distribution patterns until all local zonal schemes have been accurately correlated, either one to another or to some universal scheme for tropical and temperate areas.

The stratigraphic ranges of most planktonic foraminiferal species from the Yorktown section at Lee Creek are too long to be biostratigraphically useful (Figure 5). Those few forms that have restricted ranges are the same ones that are both rare and sporadic in occurrence (compare Figures 4 and 5).

The stratigraphic ranges of eight species and subspecies provide a basis for biostratigraphic interpretation. None of these forms has a total range zone that is restricted enough to indicate the exact relative age of the exposure. However, their concurrent range zone, based on the first appearance of five forms and the extinction level of three forms, indicates an age of late early to early late Pliocene (Figure 6). In terms of the planktonic foraminiferal zonation scheme of Blow (1969), the age of the Yorktown sediments at Lee Creek lies within an interval from just below the base of zone N19 to approximately the middle of zone N20. This corresponds to an interval from the early part of zone PL 1 to the middle part of zone PL 3 in Berggren's (1973) zonation. We do not suggest that the Yorktown section at this locality necessarily encompasses this entire span of time. It may represent only some portion of that span. However, this is the most precise interpretation that can be made on the basis of the planktonic foraminiferal fauna.

Our interpretation of the biostratigraphic position of Yorktown sediments at Lee Creek is consistent with that of Akers (1972) for the Yorktown at Rice's Pit, Virginia. It is also similar to that of Gibson (p. 363, herein). However, Gibson suggests that the age of Yorktown sediments at Lee Creek ranges well into the late Pliocene

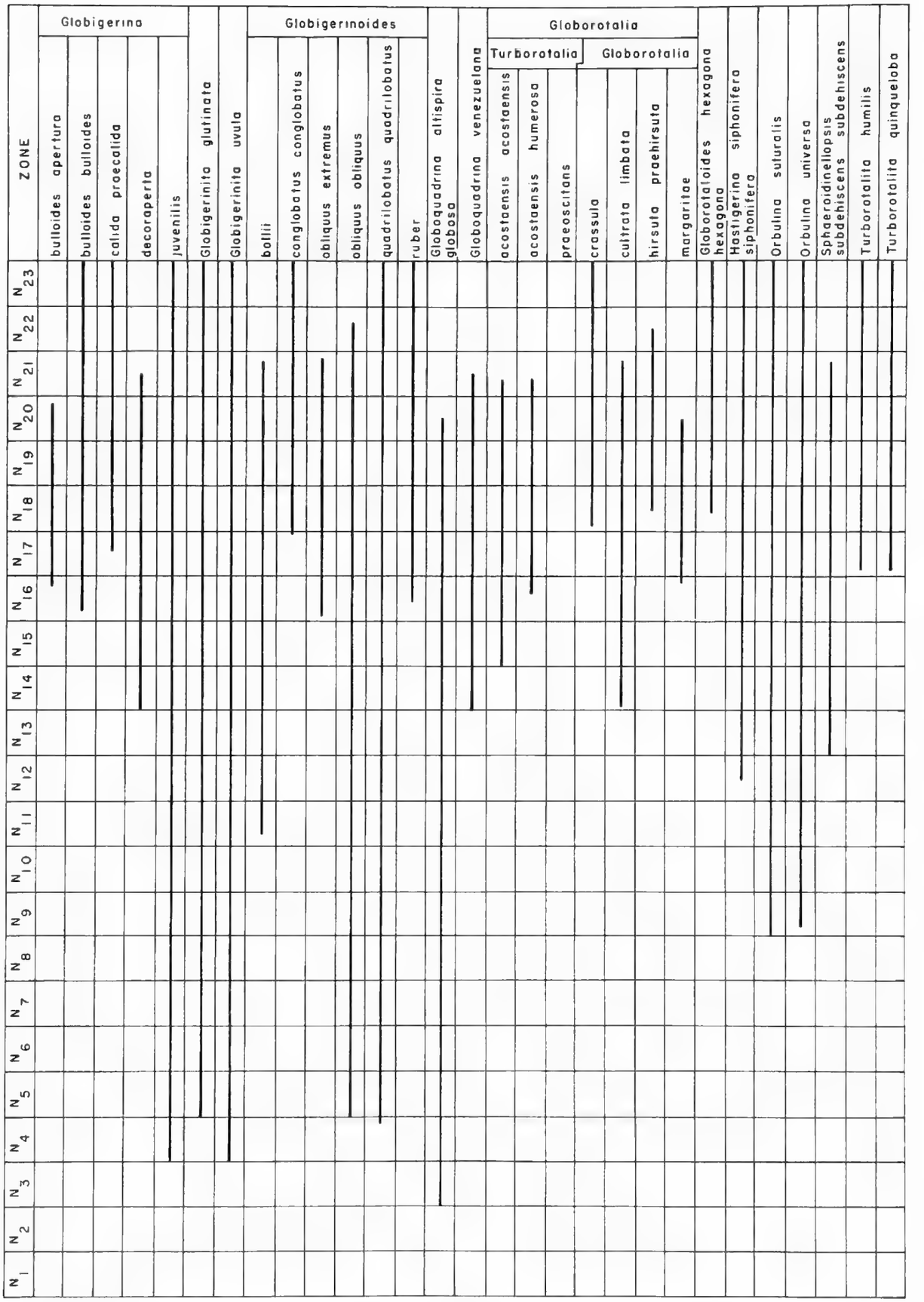


FIGURE 5.—Stratigraphic ranges of planktonic species present in the Lee Creek section (data from Parker, 1967; Blow, 1969; Postuma, 1971; Poag, 1972; Miles, 1977; Berggren, 1978).

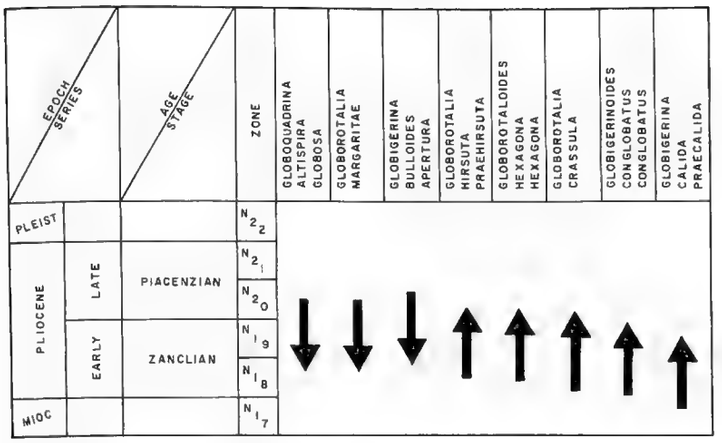


FIGURE 6.—Partial stratigraphic ranges of selected planktonic species (arrows denote continuation of range).

(Blow's zone N21, Berggren's zone PL 5 or PL 6). We find no faunal evidence for an age as young as zone N21. If one accepts the "boulder bed" as part of the Yorktown Formation, its age may range later into the Pliocene. However, the planktonic foraminiferal fauna in this unit is too impoverished (Figure 4) either to support or contradict that possibility. Thus, our biostratigraphic interpretation applies only to units 1 through 4 of Figure 2. These units at Lee Creek are, however, much older than those of Gibson's "Uppermost Yorktown" exposures along the Chowan River.

One species encountered during our study, *Globorotalia (Turborotalia) praeoscitans*, merits further comment. It is restricted to the lowermost 3 m of Yorktown sediments at Lee Creek (Figure 4). Here it is a common and conspicuous element of the fauna. Although the reasons for its sudden exclusion or extinction are unknown, it may be a reliable indicator of lower Yorktown sediments in other exposures within the middle Atlantic Coastal Plain.

## Summary

Detailed sampling of the Yorktown section at Lee Creek and careful sample preparation have made possible the recognition of greater diversity than was noted in earlier studies. An exposure generally considered to have an impoverished planktonic fauna has yielded 29 species and subspecies. The concurrent range zone of eight of the rarest of these forms provides a basis for accurate biostratigraphic interpretation. The age of this Yorktown exposure lies within an interval from just below the base of Blow's zone N19 (the early part of Berggren's zone PL 1) to the middle of his zone N20 (the middle part of Berggren's zone PL 3). According to Berggren (1978, fig. 5), this portion of the late early to early late Pliocene extends from approximately 4.8 to 3.1 million years ago. The Yorktown exposure at Lee Creek may represent only some portion of this time span, but the planktonic foraminiferal fauna cannot as yet provide any finer biostratigraphic resolution.

## Systematic Paleontology

The following section lists the species and subspecies identified during this study. A brief discussion of occurrence in the Lee Creek section is included for each taxon. The accompanying synonymies are brief, but distinguishing morphologic characters are mentioned in order to clarify the authors' concept of some of the taxa. Because the taxonomy of this paper follows Blow (1969) and Akers (1972), these references can be consulted for more extensive synonymies and more detailed discussions. Stratigraphic distribution is discussed only for those forms that were most useful in the biostratigraphic interpretation.

All illustrated specimens, with the exception of two that were lost subsequent to photography, have been designated as hypotypes and are deposited at the National Museum of Natural History, Smithsonian Institution. The USNM catalog numbers include 306816 through 306877.

Order FORAMINIFERIDA Eichwald, 1830
Superfamily GLOBIGERINACEA Carpenter, Parker, and Jones, 1862
Family GLOBIGERINIDAE Carpenter, 1862
Genus *Globigerina* d'Orbigny, 1826
Genus *Globigerinita* Bronnimann, 1951
Genus *Globigerinoides* Cushman, 1927
Genus *Globoquadrina* Finley, 1947
Genus *Orbulina* d'Orbigny, 1839
Genus *Sphaeroidinellopsis* Banner and Blow, 1959

Family GLOBOROTALIIDAE Cushman, 1927
Genus *Globorotalia* Cushman, 1927
Genus *Globorotaloides* Bolli, 1957
Genus *Turborotalita* Banner and Blow, 1962
Genus *Hastigerina* Thomson, 1876

## Genus *Globigerina* d'Orbigny, 1826

### *Globigerina bulloides apertura* Cushman

PLATE 1: FIGURES 1–3

*Globigerina apertura* Cushman, 1918:57, pl. 12: fig. 8a–c.

*Globigerina bulloides apertura* is characterized by its very large, semicircular aperture. Although this form is considered to be a subspecies of *G. bulloides*, it has a remarkably stable morphology (Blow, 1969:317). Among those forms from the Yorktown Formation at Lee Creek that are biostratigraphically useful, *G. bulloides apertura* is the one most frequently encountered. It varies from rare to common in well-preserved samples; it is absent only in horizons altered by solution. The last appearance of this subspecies occurs in the middle to late part of Blow's zone N20.

Figured hypotypes: USNM 306816, 306817, 306818.

### *Globigerina bulloides bulloides* d'Orbigny

PLATE 1: FIGURE 4

*Globigerina bulloides* d'Orbigny.—Akers, 1972:48, pl. 14: fig. 4, pl. 30: fig. 2, pl. 31: fig. 2, pl. 34: fig. 1, pl. 37: fig. 3, pl. 41: fig. 1, pl. 47: figs. 1, 2, pl. 52: fig. 4, pl. 57: fig. 3.

*Globigerina bulloides bulloides* is the numerically dominant planktonic foraminifer in every Yorktown sample from Lee Creek. It comprises 70 to 80 percent of the assemblage in well-preserved samples. In several of the samples altered by solution it is the only form present. Although *G. bulloides bulloides* is not biostratigraphically meaningful to this study, its dominance throughout the section indicates that cool water conditions existed during the entire Yorktown depositional sequence.

Figured hypotype: USNM 306819.

### *Globigerina calida praecalida* Blow

PLATE 1: FIGURES 5–7

*Globigerina calida praecalida* Blow, 1969:380, pl. 13: figs. 6, 7, pl. 14: fig. 3.

Specimens from Lee Creek compare well with Blow's figures and description, particularly with regard to the lack of radial elongation of chambers, the less widely open umbilicus, the smaller extraumbilical extent of the aperture and the lack of a clear approach to planispirality. All of these characters serve to distinguish *G. calida praecalida* from *G. calida calida* Parker. Specimens from Lee Creek have 4½ to 5 chambers in the final whorl, as compared to the 4 that Blow describes as typical. However, all other test characters correspond with his description. Large, well-preserved specimens are rare and occur sporadically throughout the section. *G. calida praecalida* first appears in the late part of Blow's zone N17.

Figured hypotypes: USNM 306820, 306821, 306822.

### *Globigerina decoraperta* Takayanagi and Saito

PLATE 1: FIGURES 10–12

*Globigerina druryi decoraperta* Takayanagi and Saito.—Akers, 1972:50; pl. 14: fig. 3, pl. 29: fig. 1, pl. 31: fig. 3, pl. 34: fig. 3, pl. 37: fig. 2.

This small, trochospiral species is rare, but it occurs in nearly all samples except those altered by solution.

Figured hypotypes: USNM 306825, 306826, 306827.

### *Globigerina juvenilis* Bolli

PLATE 1: FIGURES 8, 9

*Globigerina juvenilis* Bolli, 1957:110, pl. 24: figs. 5a–c, 6.

*Globigerina juvenilis* can be readily distinguished from other species present at Lee Creek by its small umbilicus and low, slitlike aperture with a thin but distinct lip. Its occurrence in our samples closely parallels that of *G. decoraperta*.

Figured hypotypes: USNM 306823, 306824.

## Genus *Globigerinita* Brönnimann, 1951

### *Globigerinita glutinata* (Egger)

PLATE 1: FIGURES 13–15

*Globigerinita glutinata* (Egger).—Akers, 1972:70, pl. 21: fig. 2, pl. 33: fig. 3, pl. 38: fig. 2.

*Globigerinita glutinata* is the second most abundant planktonic foraminifer in the Yorktown sediments at Lee Creek. Its absence in eight samples is probably related to destruction by solution. Because it is the most cosmopolitan of living planktonic foraminiferal species (Bé, 1959, figs. 21, 22), its abundance in our samples is consistent with the interpretation of the Yorktown fauna as indicative of cool waters.

Figured hypotypes: USNM 306828, 306829.

### *Globigerinita uvula* (Ehrenberg)

PLATE 1: FIGURES 16, 17

*Globigerinita uvula* (Ehrenberg).—Akers, 1972:72, pl. 1: fig. 2, pl. 15: fig. 2, pl. 29: fig. 3, pl. 52: fig. 1.

This small, high-spired species is rare and occurs sporadically throughout portions of the section where solution has been minimal.

Figured hypotypes: USNM 306830, 306831.

## Genus *Globigerinoides* Cushman, 1927

### *Globigerinoides bollii* Blow

PLATE 2: FIGURES 1, 2

*Globigerinoides bollii* Blow, 1959:189, pl. 10: fig. 65a–c.

*Globigerinoides bollii* can be most readily distinguished from other species of the genus by its small, almost completely circular aperture and its strongly embracing chambers. It occurs in only nine samples and it is rare when present.

Figured hypotypes: USNM 306832, 306833.

### *Globigerinoides conglobatus conglobatus* (Brady)

PLATE 2: FIGURES 3, 4

*Globigerinoides conglobatus conglobatus* (Brady).—Akers, 1972:56, pl. 24: figs. 1, 2, pl. 58: figs. 1, 2.

Although large, well-developed specimens of this form are rare and occur in only seven samples, it is biostratigraphically significant because it first appears near the base of Blow's zone N18. Distinctive characters include the subquadrate outline, the long but comparatively low and gently arched aperture, and the coarse surface texture.

Figured hypotypes: USNM 306834, 306835.

### *Globigerinoides obliquus extremus* Bolli and Bermúdez

PLATE 2: FIGURES 5–7

*Globigerinoides obliquus extremus* Bolli and Bermúdez, 1965:139, pl. 1: figs. 10–12.

*Globigerinoides obliquus extremus* differs from *G. obliquus obliquus* in that the chambers of the final whorl are more strongly compressed in a lateral, oblique manner. It is present but rare in eight samples that are irregularly distributed throughout the Yorktown section.

Figured hypotypes: USNM 306836, 306837, 306838.

### *Globigerinoides obliquus obliquus* Bolli

PLATE 2: FIGURES 8–10

*Globigerinoides obliqua* Bolli, 1957:113, pl. 25: figs. 9, 10, text-fig. 21: no. 5.

Like the preceding subspecies, the later chambers of this form are compressed, albeit to a lesser extent, in a lateral, oblique manner. *G. obliquus obliquus* is present but rare in most samples where solution has not occurred.

Figured hypotypes: USNM 306839, 306840, 306841.

### *Globigerinoides quadrilobatus quadrilobatus* (d'Orbigny)

PLATE 2: FIGURES 11, 12

*Globigerinoides quadrilobatus quadrilobatus* (d'Orbigny).—Akers, 1972:62, pl. 3: fig. 4, pl. 6: fig. 2, pl. 11: figs. 2, 3, pl. 16:

fig. 4, pl. 18: fig. 1, pl. 22: fig. 1, pl. 27: fig. 2, pl. 30: fig. 3, pl. 34: fig. 4, pl. 39: fig. 2, pl. 42: fig. 3, pl. 49: fig. 1, pl. 53: fig. 3, pl. 56: fig. 2, pl. 59: fig. 1.

Well-developed specimens of this long-ranging species occur in samples where solution has been minimal. It is, however, rare in all but one of these samples.

Figured hypotypes: USNM 306842, 306843.

### *Globigerinoides ruber* (d'Orbigny)

PLATE 2: FIGURES 13, 14

*Globigerina rubra* d'Orbigny, 1839:82, pl. 4: figs. 12–14.

*Globigerinoides ruber* is present in most samples, except those taken from horizons showing obvious effects of solution. Because it is one of the most dependable warm-water indicator species, its low relative abundances in our samples, even those showing no evidence of solution, suggest that the Yorktown sea was characterized by cool temperatures.

Figured hypotypes: USNM 306844, 306845.

## Genus *Globoquadrina* Finley, 1947

### *Globoquadrina altispira globosa* Bolli

PLATE 4: FIGURES 1–3

*Globoquadrina altispira globosa* Bolli, 1957:111, pl. 24: figs. 9, 10.

This form accounts for less than 1 percent of the planktonic assemblage in six samples, five from the lower part and one from the upper middle part of the Yorktown section. Its absence throughout the remainder of the section is probably due to its low initial abundance in waters of the Yorktown sea. Distinguishing characters include the spherical chambers and the moderately wide but very deep umbilicus. Specimens of this species from Lee Creek lack the very high spire that characterizes *G. altispira altispira.* Parker (1967:165) and Akers (1972:88) state that there is no special stratigraphic significance in the separation of these two subspecies. *G. altispira globosa* is biostratigraphically important because its last appearance is in the middle of Blow's zone N20. According to Berggren (1978, figs. 5, 14), the *G. altispira* extinction level appears to be constant over wide geographic areas.

Figured hypotypes: USNM 306866, 306867, 306868.

### *Globoquadrina venezuelana* (Hedberg)

PLATE 4: FIGURES 4, 5

*Globigerina venezuelana* Hedberg, 1937:681, pl. 92: fig. 7a,b.

Most specimens from Lee Creek have four inflated chambers in the final whorl, the last chamber being somewhat wider and more embracing than previous chambers. Small umbilical, toothlike projections are present on some specimens. This species comprises less than 1 percent of the planktonic assemblage in three samples from the lower and middle parts of the Yorktown section.

Figured hypotypes: USNM 306869, 306870.

## Genus *Orbulina* d'Orbigny, 1839

### *Orbulina suturalis* Brönnimann

PLATE 4: FIGURE 8

*Orbulina suturalis* Brönnimann [part], 1951:135, text-fig. 2: nos. 1, 2, 5–8, 10, text-fig. 3: nos. 3–8, 11, 13–16, 18, 20–22, text-fig. 4: nos. 2–4, 7–12, 15, 16, 19–22.

*Orbulina suturalis* occurs in seven samples that are irregularly distributed through the lower and middle portions of the Yorktown section. It never comprises more than 1 percent of the planktonic fauna.

Figured hypotype: USNM 306872.

### *Orbulina universa* d'Orbigny

PLATE 4: FIGURE 9

*Orbulina universa* d'Orbigny, 1839:2, pl. 1: fig. 1.

*Orbulina universa* occurs sporadically throughout the lower and middle portions of the Yorktown

section. Specimens are rare and often show minor effects of solution.

Figured hypotype: USNM 306873.

## Genus *Sphaeroidinellopsis* Banner and Blow, 1959

### *Sphaeroidinellopsis subdehiscens subdehiscens* Blow

PLATE 4: FIGURES 10, 11

*Sphaeroidinella dehiscens subdehiscens* Blow, 1959:195, pl. 12: figs. 71, 72.

In all specimens from the Lee Creek section, the smooth outer cortex of this form has been destroyed, thus exposing the thick and coarsely perforate inner part of the wall. It is present but rare in most samples from stratigraphic intervals where solution has been minimal.

Figured hypotype: USNM 306874.

## Genus *Globorotalia* Cushman, 1927

### *Globorotalia (Turborotalia) acostaensis acostaensis* Blow

PLATE 3: FIGURES 1–3

*Globorotalia acostaensis* Blow, 1959:208, pl. 17: fig. 106a–c, 107.

Among the globorotaliids present in the Lee Creek section, this form, though it is always rare, occurs in the greatest number of samples. Its smaller umbilicus, more nearly planar spiral side, and greater displacement of the final chamber towards the umbilical side (partially obscuring the aperture when specimens are viewed from that side) serve to distinguish it from *G. acostaensis humerosa.*

Figured hypotypes: USNM 306849, 306850, 306851.

### *Globorotalia (Turborotalia) acostaensis humerosa* Takayanagi and Saito

PLATE 3: FIGURES 4–6

*Globorotalia acostaensis humerosa* Takayanagi and Saito.—Akers, 1972:108, pl. 17: fig. 4, pl. 19: fig. 3, pl. 25: fig. 2, pl. 26: fig. 3, pl. 28: fig. 2, pl. 36: fig. 2, pl. 40: fig. 2, pl. 44: fig. 2, pl. 48: fig. 1, pl. 54: fig. 2, pl. 57: fig. 1.

*Globorotalia acostaensis humerosa* occurs in nearly as many samples as does *G. acostaensis acostaensis.* It is a common member of the planktonic assemblage in three samples from the lower part of the Yorktown section.

Figured hypotypes: USNM 306852, 306853, 306854.

### *Globorotalia (Turborotalia) praeoscitans* Akers

PLATE 3: FIGURES 7–9

*Globorotalia praeoscitans* Akers, 1972:116, pl. 32: fig. 3, pl. 36: fig. 3, pl. 50: fig. 2, pl. 51: fig. 3.

*Globorotalia praeoscitans* was described from the Yorktown sediments at Rice's Pit, Virginia, and at the same time was reported from the Jackson Bluff Formation (Akers, 1972:118). The abrupt inflation, both lateral and vertical, of the final chamber and the large semicircular aperture make it a distinctive and conspicuous element of the Yorktown planktonic assemblage. It is common within and restricted to the lowermost 3 m of the Lee Creek section, suggesting that it may be a useful marker for the lower Yorktown Formation elsewhere in the middle Atlantic Coastal Plain.

Figured hypotypes: USNM 306855, 306856, 306857.

### *Globorotalia (Globorotalia) crassula* Cushman and Stewart

PLATE 3: FIGURES 10–12

*Globorotalia crassula* Cushman and Stewart.—Blow, 1969:397, pl. 5: figs. 4–9.

The taxonomy of the crassiform globorotaliids presents many difficulties (Cifelli and Glaçon, 1979). Rare specimens referable to *Globorotalia crassula* are present in five samples from Yorktown sediments at Lee Creek. Three of these samples are from the lower part of the section; two, from the upper part. *G. crassula* first appears just above the base of Blow's zone N18.

Figured hypotypes: USNM 306858, 306859, 306860.

### *Globorotalia (Globorotalia) cultrata limbata* (Fornasini)

PLATE 3: FIGURES 19, 20

*Globorotalia cultrata limbata* (Fornasini).—Akers, 1972:98, pl. 33: fig. 2.

*Globorotalia cultrata limbata* differs from other globorotaliids present at Lee Creek in having an acute, strongly carinate periphery and a smooth surface, except for a pustulose area on the umbilical side of the first chamber of the final whorl. This moderately long-ranging form was recovered from only two samples, both of which are from the middle part of the section.

The figured specimen was lost subsequent to photography.

### *Globorotalia (Globorotalia) hirsuta praehirsuta* Blow

PLATE 3: FIGURES 13–15

*Globorotalia hirsuta praehirsuta* Blow, 1969:400, pl. 43: figs. 3–7.

*Globorotalia hirsuta praehirsuta* differs from *G. hirsuta hirsuta* in that the intercameral sutures of the spiral side are more strongly recurved in the posterior direction, the intercameral sutures of the ventral side are less deeply incised, and the test is more nearly plano-convex. Specimens from Lee Creek show some variation in the latter character but are otherwise consistent with Blow's description. *G. hirsuta praehirsuta* occurs in seven samples that range from the lower to the middle part of the Yorktown section. According to Blow (1969), *G. hirsuta praehirsuta* develops from *G. margaritae* in the middle part of zone N18, but both forms co-exist through zone N19. The Yorktown section at Lee Creek lies within this zone of stratigraphic overlap. *G. hirsuta praehirsuta* eventually gives rise to *G. hirsuta hirsuta* in zone N22.

Figured hypotypes: USNM 306861, 306862, 306863.

### *Globorotalia (Globorotalia) margaritae* Bolli and Bermúdez

PLATE 3: FIGURES 16–18

*Globorotalia (Globorotalia) margaritae* Bolli and Bermúdez, 1965:139, pl. 1: figs. 16–18.

*Globorotalia margaritae* occurs in seven samples from the middle part of the Yorktown section at Lee Creek. According to Poag (1972:509), the last appearance of *G. margaritae* in the western North Atlantic coincides with the end of Blow's zone N19. The extinction level of *G. margaritae* has been interpreted as constant over wide areas (Berggren, 1978, figs. 4, 5, 14). However, Parker (1967:180) stated that this species ranges into Blow's zone N20 in sediments from the tropical Indo-Pacific. Its range in the Caribbean and Gulf of Mexico extends into sediments equivalent to zone N20 (Lamb and Beard, 1972:45, 53, 54). In addition, one of us (Akers) has recently encountered it in sediments belonging within zone N20. In light of this evidence, the biostratigraphic interpretation of Snyder et al. (1980) has been slightly modified.

*G. margaritae* can be distinguished from *G. hirsuta praehirsuta* by its ventral side concavity, its more convex spiral side, and its more acute and thinly keeled periphery. Comparison with the three subspecies described as members of the *G. margaritae* lineage by Cita (1973) reveals that specimens from Lee Creek most closely resemble *G. margaritae margaritae*. Our material contains dextral and sinistral forms in approximately equal abundances, but specimens are too few for coiling direction ratios to be meaningful.

Figured hypotypes: USNM 306864, 306865.

## Genus *Globorotaloides* Bolli, 1957

### *Globorotaloides hexagona hexagona* (Natland)

PLATE 2: FIGURES 15–17

*Globorotaloides hexagona hexagona* (Natland).—Akers, 1972:124, pl. 28: fig. 1.

The most distinctive morphologic feature of this form is its unique wall structure, which consists of hexagonal pits. *G. hexagona* occurs in several samples near the base of the Yorktown sec-

tion and again in several samples clustered in the middle part of the section. It first appears in the latter part of Blow's zone N18.

Figured hypotypes: USNM 306846, 306847, 306848.

### Genus *Turborotalita* Banner and Blow, 1962

### *Turborotalita humilis* (Brady)

PLATE 4: FIGURES 14, 15

*Truncatulina humilis* Brady.—Barker, 1960:194, pl. 94: fig. 7.

Except that the test is slightly more inflated, specimens from the Yorktown Formation at Lee Creek compare closely to the concept of this species as it has been applied in the literature. It is present but rare in five samples ranging from the base to the upper part of the section.

Figured hypotype: USNM 306877.

### *Turborotalita quinqueloba* (Natland)

PLATE 4: FIGURES 12, 13

*Turborotalita quinqueloba* (Natland).—Akers, 1972:122, pl. 41: fig. 1, pl. 45: fig. 1.

*Turborotalita quinqueloba* can be easily identified by its extended final chamber and overhanging apertural lip that almost cover the umbilicus. It is present in most samples except those from horizons characterized by solution.

Figured hypotypes: USNM 306875, 306876.

### Genus *Hastigerina* Thomson, 1876

### *Hastigerina siphonifera siphonifera* (d'Orbigny)

PLATE 4: FIGURES 6, 7

*Globigerina siphonifera* d'Orbigny, 1839:83, pl. 4: figs. 15–18.

The planispiral or nearly planispiral coiling of this form serves to distinguish it from all other species present in the Lee Creek section. It is irregularly distributed from the lower through the middle part of the section.

Figured hypotype: USNM 306871 (Plate 4: figure 7). The other figured specimen (Plate 4: figure 6) was lost subsequent to photography.

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## PLATE 1

1–3. *Globigerina bulloides apertura* Cushman, hypotypes: 1, USNM 306816, umbilical view, sample 40; 2, USNM 306817, spiral view, sample 23; 3, USNM 306818, umbilical view, sample 23.

4. *Globigerina bulloides bulloides* d'Orbigny, hypotype, USNM 306819, umbilical view, sample 35.

5–7. *Globigerina calida praecalida* Blow, hypotypes: 5, USNM 306820, umbilical view, sample 23; 6, USNM 306821, spiral view, sample 23; 7, USNM 306822, edge view, sample 23.

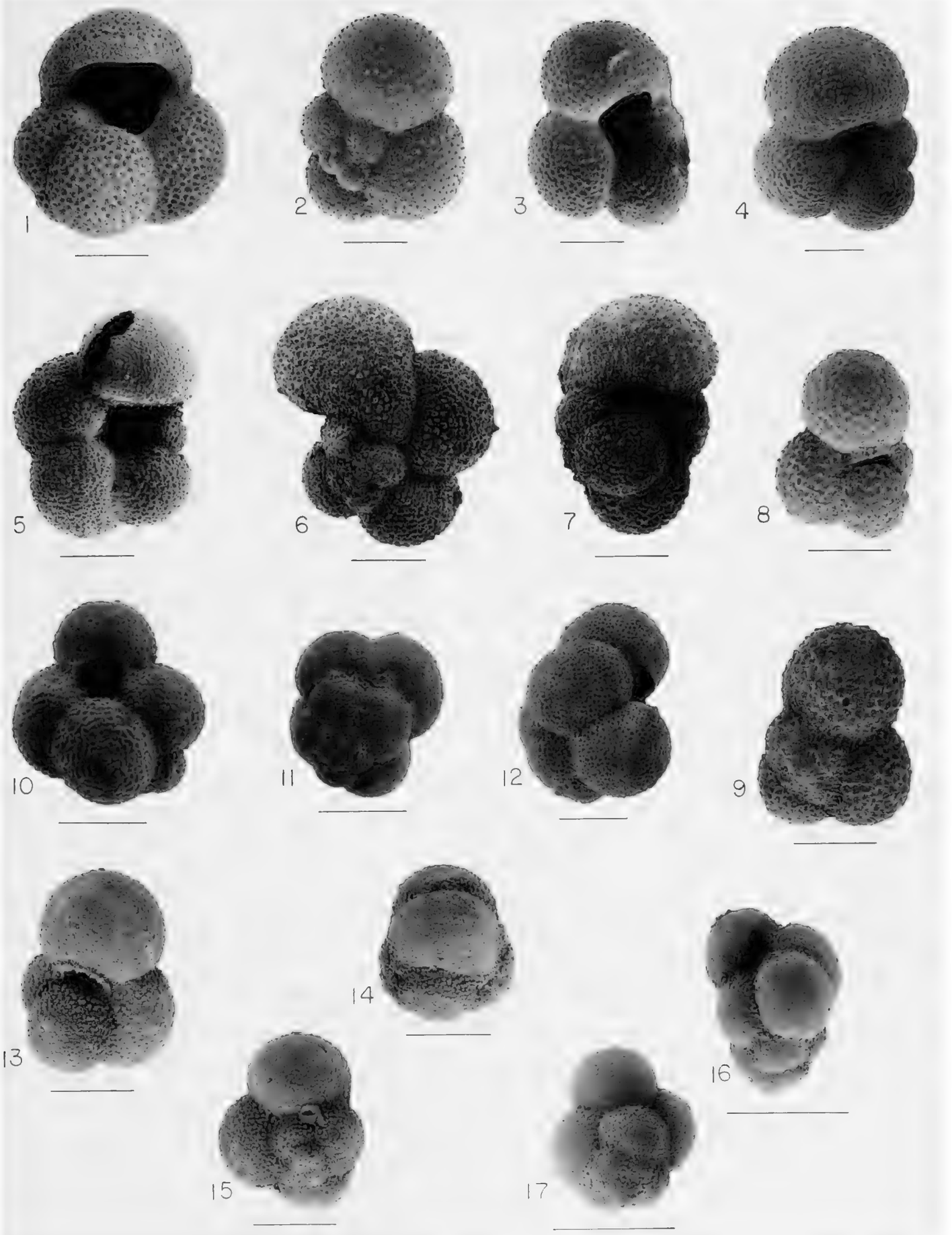
8, 9. *Globigerina juvenilis* Bolli, hypotypes: 8, USNM 306823, umbilical view, sample 15; 9, USNM 306824, spiral view, sample 15.

10–12. *Globigerina decoraperta* Takayanagi and Saito, hypotypes: 10, USNM 306825, umbilical view, sample 35; 11, USNM 306826, spiral view, sample 35; 12, USNM 306827, edge view, sample 35.

13–15. *Globigerinita glutinata* (Egger), hypotypes: 13, USNM 306828, umbilical view, sample 15; 14, USNM 306829, umbilical view, sample 15; 15, USNM 306829, spiral view, sample 15.

16, 17. *Globigerinita uvula* (Ehrenberg), hypotypes: 16, USNM 306830, apertural view, sample 35; 17, USNM 306831, spiral view, sample 35.

Each scale equals 100 microns.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## PLATE 2

1, 2. *Globigerinoides bollii* Blow, hypotypes: 1, USNM 306832, umbilical view, sample 35; 2, USNM 306833, spiral view, sample 35.

3, 4. *Globigerinoides conglobatus conglobatus* (Brady), hypotypes: 3, USNM 306834, umbilical view, sample 40; 4, USNM 306835, spiral view, sample 40.

5–7. *Globigerinoides obliquus extremus* Bolli and Bermúdez, hypotypes: 5, USNM 306836, umbilical view, sample 37; 6, USNM 306837, spiral view, sample 35; 7, USNM 306838, edge view, sample 41.

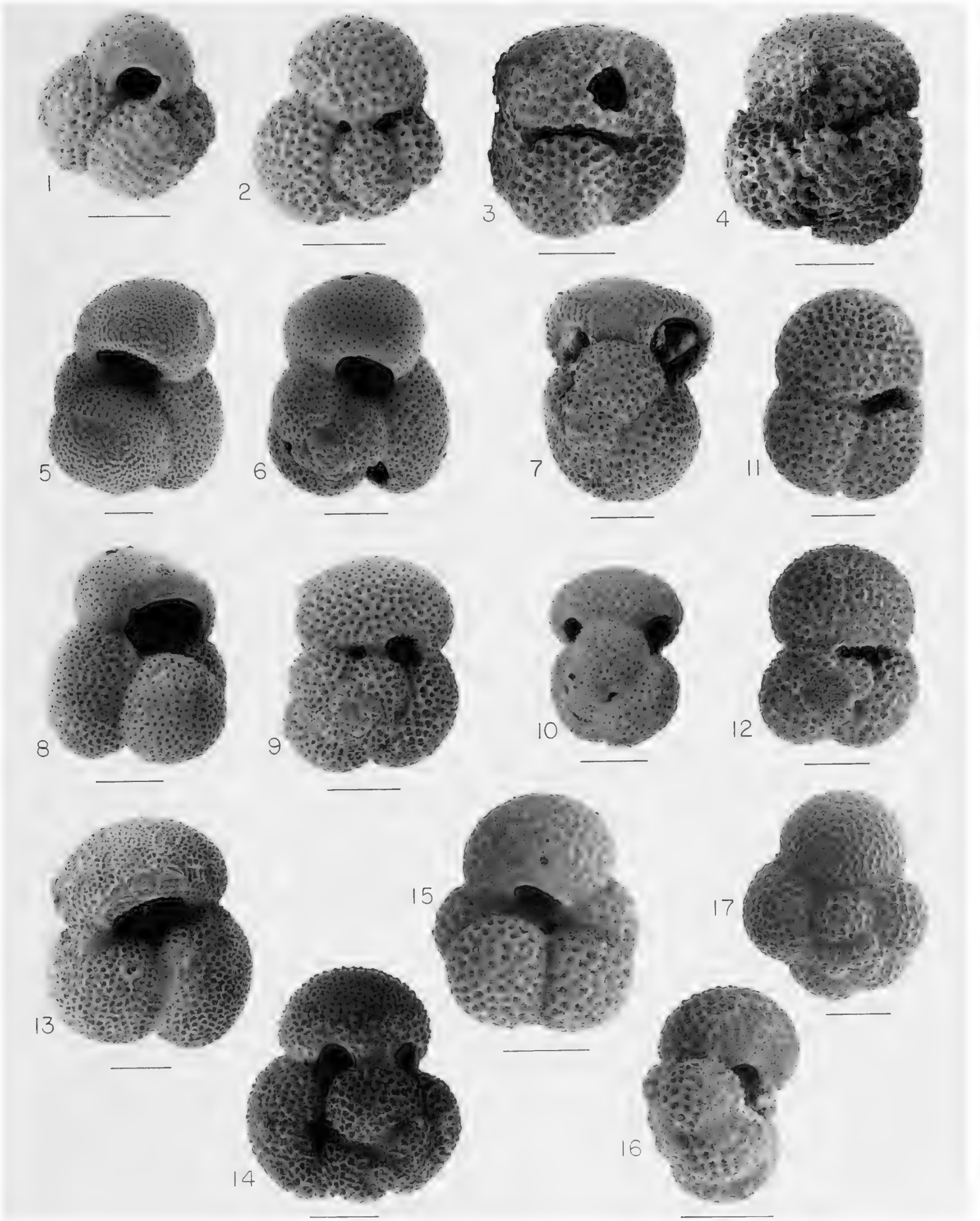
8–10. *Globigerinoides obliquus obliquus* Bolli, hypotypes: 8, USNM 306839, umbilical view, sample 35; 9, USNM 306840, spiral view, sample 35; 10, USNM 306841, edge view, sample 35.

11, 12. *Globigerinoides quadrilobatus quadrilobatus* (d'Orbigny), hypotypes: 11, USNM 306842, umbilical view, sample 40; 12, USNM 306843, spiral view, sample 40.

13, 14. *Globigerinoides ruber* (d'Orbigny), hypotypes: 13, USNM 306844, umbilical view, sample 23; 14, USNM 306845, spiral view, sample 23.

15–17. *Globorotaloides hexagona hexagona* (Natland), hypotypes: 15, USNM 306846, umbilical view, sample 35; 16, USNM 306847, edge view, sample 40; 17, USNM 306848, spiral view, sample 23.

Each scale equals 100 microns.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## PLATE 3

1–3. *Globorotalia* (*Turborotalia*) *acostaensis acostaensis* Blow, hypotypes: 1, USNM 306849, umbilical view, sample 35; 2, USNM 306850, spiral view, sample 35; 3, USNM 306851, edge view, sample 15.

4–6. *Globorotalia* (*Turborotalia*) *acostaensis humerosa* Takayanagi and Saito, hypotypes: 4, USNM 306852, umbilical view, sample 35; 5, USNM 306853, spiral view, sample 35; 6, USNM 306854, edge view, sample 35.

7–9. *Globorotalia* (*Turborotalia*) *praeoscitans* Akers, hypotypes: 7, USNM 306855, umbilical view, sample 35; 8, USNM 306856, spiral view, sample 35; 9, USNM 306857, edge view, sample 35.

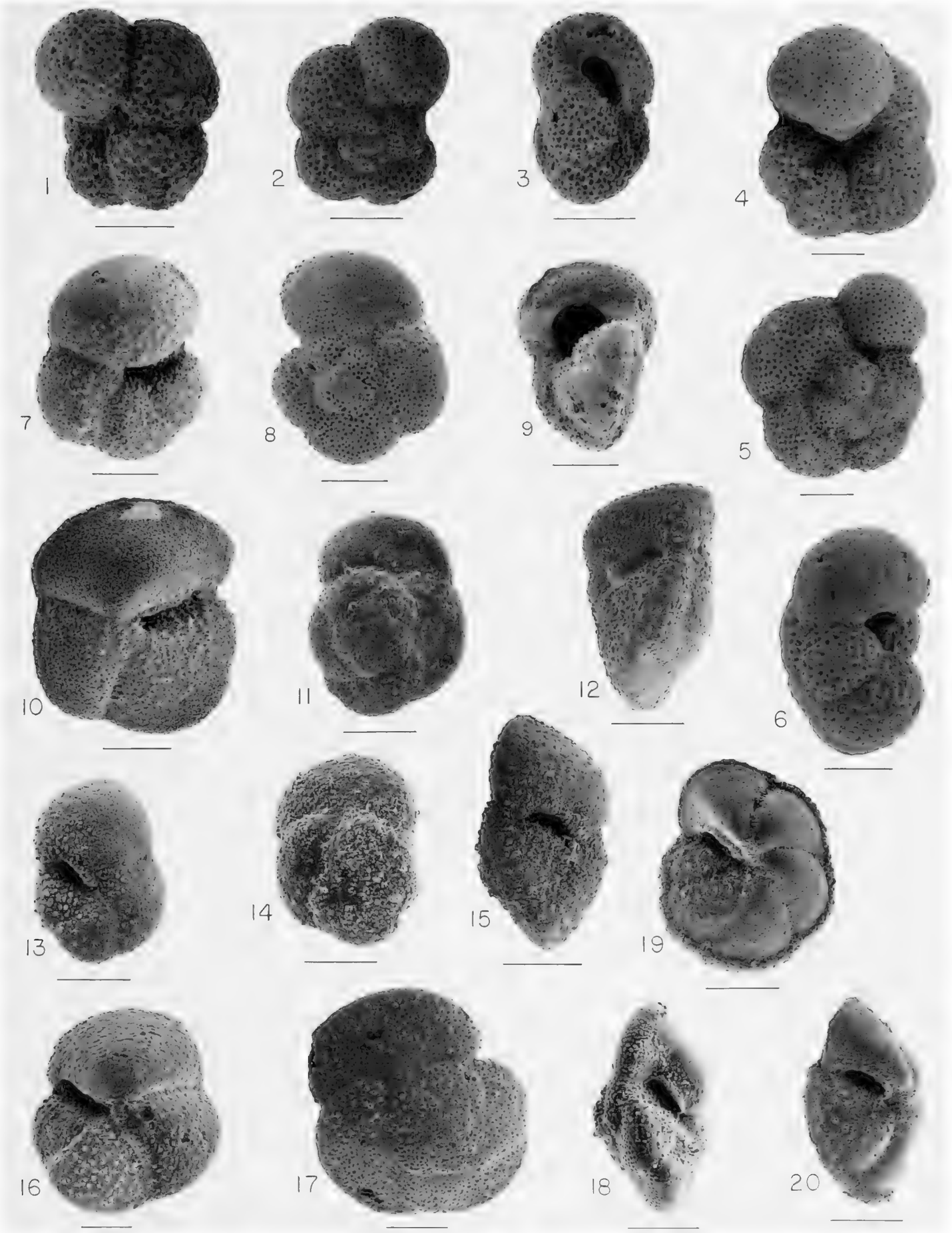
10–12. *Globorotalia* (*Globorotalia*) *crassula* Cushman and Stewart, hypotypes: 10, USNM 306858, umbilical view, sample 40; 11, USNM 306859, spiral view, sample 35; 12, USNM 306860, edge view, sample 35.

13–15. *Globorotalia* (*Globorotalia*) *hirsuta praehirsuta* Blow, hypotypes: 13, USNM 306861, umbilical view, sample 41; 14, USNM 306862, spiral view, sample 21; 15, USNM 306863, edge view, sample 16.

16–18. *Globorotalia* (*Globorotalia*) *margaritae* Bolli and Bermúdez, hypotypes: 16, USNM 306864, umbilical view, sample 23; 17, USNM 306864, spiral view, sample 23; 18, USNM 306865, edge view, sample 25.

19, 20. *Globorotalia* (*Globorotalia*) *cultrata limbata* (Fornasini) (specimen lost subsequent to photography): 19, umbilical view, sample 16; 20, edge view, sample 16.

Each scale equals 100 microns.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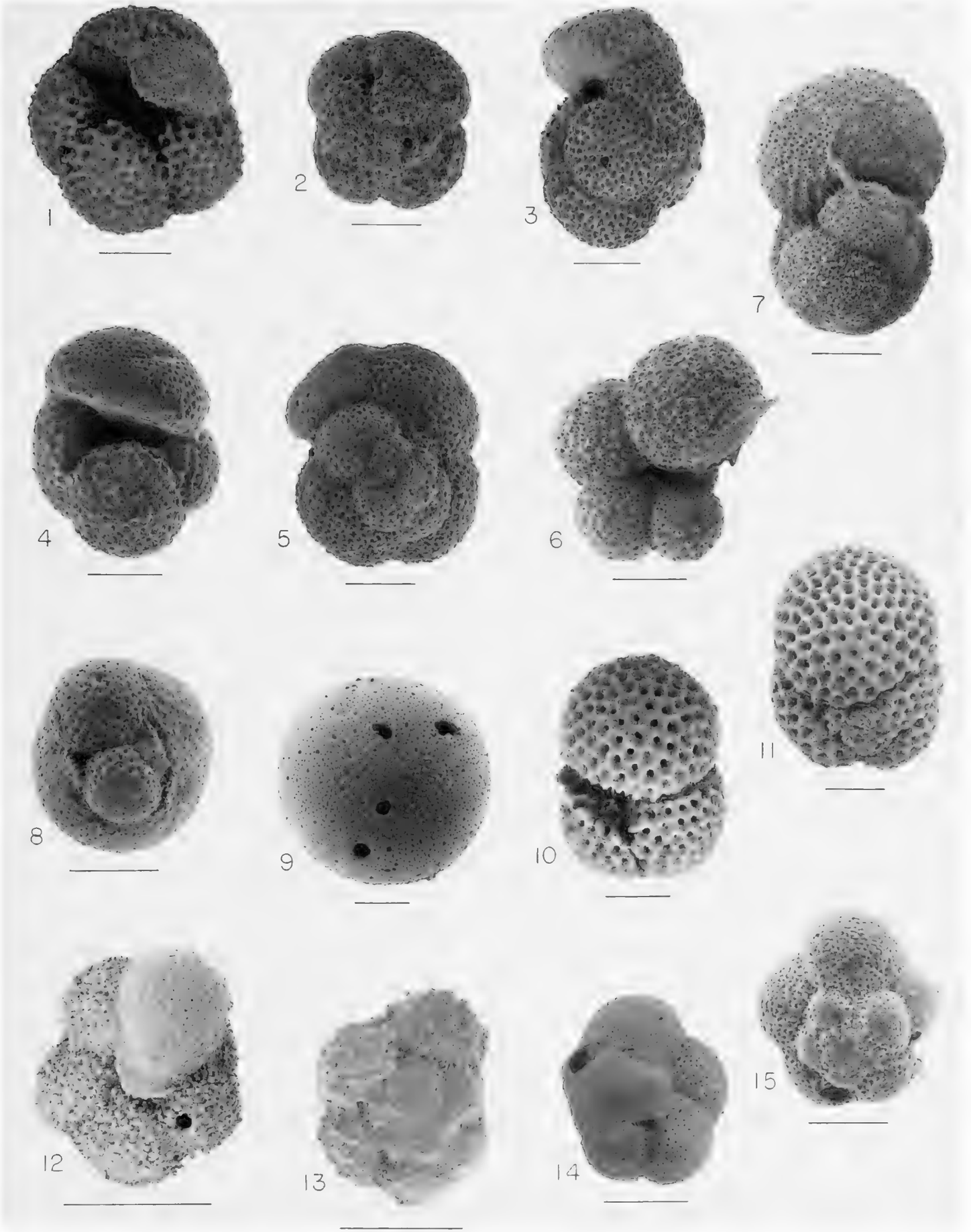
## PLATE 4

1–3. *Globoquadrina altispira globosa* Bolli, hypotypes: 1, USNM 306866, umbilical view, sample 40; 2, USNM 306867, spiral view, sample 40; 3, USNM 306868, edge view, sample 34.
4, 5. *Globoquadrina venezuelana* (Hedberg), hypotypes: 4, USNM 306869, umbilical view, sample 36; 5, USNM 306870, spiral view, sample 36.
6, 7. *Hastigerina siphonifera siphonifera* (d'Orbigny): 6, specimen lost subsequent to photography, side view, sample 35; 7, hypotype, USNM 306871, edge view, sample 15.
8. *Orbulina suturalis* Bronnimann, hypotype, USNM 306872, bottom view, early chambers, sample 23.
9. *Orbulina universa* d'Orbigny, hypotype, USNM 306873, top view, final chamber, sample 23.
10, 11. *Sphaeroidinellopsis subdehiscens subdehiscens* Blow, hypotypes: 10, USNM 306874, umbilical view, sample 40; 11, USNM 306874, spiral view, sample 40.
12, 13. *Turborotalita quinqueloba* (Natland), hypotypes: 12, USNM 306875, umbilical view, sample 15; 13, USNM 306876, spiral view, sample 35.
14, 15. *Turborotalita humilis* (Brady), hypotypes: 14, USNM 306877, umbilical view, sample 23; 15, USNM 306877, spiral view, sample 23.

Each scale equals 100 microns.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# The Lee Creek Enigma, *Mclellania aenigma*, a New Taxon in Fossil Cirrhipedia

*Druid Wilson*

ABSTRACT

An enigmatic fossil, *Mclellania aenigma* Wilson, new subfamily (Balanidae: Mclellaniinae), genus, and species, found embedded in the shell of the bivalve *Mercenaria*, occurs in the Pliocene Croatan Formation of Lee Creek, in strata of Yorktown age in North Carolina, Virginia, and Florida, and in the Miocene Choptank Formation of Maryland. The enigmas are calcitic in contrast to the aragonitic shells of *Mercenaria*. The pattern of growth shows that they are produced in the living shell and are not a result of subsequent diagenetic fossilization. Because of characters in common, they are considered to be thoracican cirripeds, probably parasites. A nomenclatorial revision of the principal host-*Mercenaria* species resurrects *Mercenaria corrugata* (Lamarck, 1818).

## Introduction

An unknown, unidentifiable organism rarely remains an enigma once its habitat is known. Not so in the case of the Lee Creek "curiosities." Specimens of these fossils were first collected as discrete float at Lee Creek and sent to the Smithsonian Institution by Jack McLellan of Texasgulf Inc. They were passed around to paleontologists and finally dismissed by most as not, or probably not, organic. Some of us, however, remained suspicious or convinced that they were indeed organic. Later Blake Blackwelder saw a specimen fall from the interior of a shell of a fossil clam, *Mercenaria*, which he was washing. It had been embedded in the shell. Fortunately this shell was not float; it came from a collection made by the author from the Croatan (or upper) shell bed. At this time anyone who would look and hazard an opinion was asked to comment. Despite their interest and amazement, no one could recollect having seen a comparable living or fossil organism. Some, accepting the organic derivation of the specimens, maintained that these fossils were not an entity separate from the *Mercenaria*.

The specimens, eventually dubbed "enigmas," are conical or subconical calcareous bodies composed of alternate light and dark layers; the conical surface has a crystalline appearance, which contributed to the consideration that they might be inorganic. The opposite, subplanar, surface is slightly concave and more or less smooth. The specimens are about evenly divided between "singles" and "multiples," which comprise more than one individual and are described as "aggregates." A certain likeness between the alternate light and dark layers of the enigmas and the bases of some fossil barnacles is apparent. Thus, the possibility that the enigmas were calcitic (like most thoracican cirripeds) rather than aragonitic (like the shell of *Mercenaria* and many other mollusks, both bivalves and gastropods), prompted me to discuss the determination of the mineralogy of the specimens with Zalman Altshuler. Subsequently Cristina Silber made determi-

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nations of five subsamples from different areas of a single specimen (USNM 304379). The results revealed only calcite. The presence of calcite in both cirripeds and the enigmas was interesting and provocative, but it did not rule out the possibility of production by genetically altered mercenarias, pathologic microorganisms infecting the clams, or diagenesis within the *Mercenaria* shells during fossilization. One fact seems contraindicative to genetic production of enigmas. The enigmas are paired in neither of the only two specimens of double-valved "infected" mercenarias. Paratype USNM 305117 has an enigma only in the left valve of the pair. Paratype USNM 305126 has unpaired aggregates in both valves. It would be highly unusual if genetically produced characters in each valve were not mirror images.

At the first opportunity, a search was made for enigmas in specimens of *Mercenaria* from the Croatan Formation at Lee Creek, but none were found. Later, all mercenarias in the Cenozoic systematic collection were searched and in those of Yorktown age many enigmas were found. Further search in related stratigraphic collections turned up still more examples. In all, some forty specimens have been recovered.

All mercenarias in the collection of Recent mollusks in the USNM collections were examined, but no enigmas were found. Although museum specimens of *Mercenaria* are numerous, eventual discovery of living enigmas is not precluded. They should be searched for in large populations of living *Mercenaria* at the southern limits of its range. It is known that Yorktown age beds contain warmer water assemblages than the Recent faunal assemblages in the same latitudes. Jung (1977:846–847) has reported a Pinecrest (Yorktown age) species, *Trigonostoma* (*Extractrix*) *hoerlei* Olsson, of Florida, from the Pliocene of Venezuela, which had already been reported in the Yorktown Formation by Campbell et al. (1975:114) from as far north as Chuckatuck, Virginia. The Pinecrest has a large faunal assemblage of decidedly warm water affinities.

One of the specimens (USNM 305107) (Plate 2: figure 2) from the Yorktown of North Carolina shows beyond any doubt that the enigmas were produced in the mercenarias during life. The normally expanding growth of the pallial sinus of the *Mercenaria* has overrun an edge of a large enigma. Further consideration of diagenesis as producing the enigmas seemed unnecessary.

Parts of the early noncalcareous (cyprid) stage of Recent barnacles have been found preserved beneath their adherent bases, according to Newman, Zullo, and Withers (1969:217). The chance of their occurring as fossils under the conical basis of an enigma is probably remote. However, a consideration of the amino acids of major higher taxa may also support the conclusion reached here. Each major higher taxon produces its own characteristic amino acids, which may be preserved in fossilized hard parts of organisms. An analysis might determine whether or not the enigmas contain arthropodan amino acids.

No parallel has been inferred between the "cancerous panopes" that occur in the Choptank Miocene of Maryland and enigmas. Some specimens of *Panopea americana* (Conrad) contain conspicuous, dark, amorphous, calcareous masses protruding from under the umbones inside their shells. Cristina Silber (pers. comm.) has determined by X-ray diffraction that the dark amorphous mass is composed of calcite. *Panopea* is one of the bivalves whose shell is aragonitic. A sectioned shell (USNM 305105) shows that the mass was produced during the life of the panope. No explanation of this interesting anomaly has been deduced.

The parallel between certain balanid cirripeds and the enigmas led to a search of the cirriped literature. An illustration (Darwin, 1854, pl. 9) of species of the balanid genus *Acasta* led to specimens of *Acasta cyathus* Darwin in the Smithsonian collection of Recent cirripeds. The basis of *Acasta cyathus* (Plate 1: figure 11) was indeed a homologue of the enigmas. Morphologically they were too much alike to be coincidental. According to Darwin (1854:305), species of *Acasta* not only are embedded in, but are attached to, the fibers of sponges. Thus, the enigmas and the bases of species of *Acasta* are morphologic and functional

equivalents. They are both attached to and embedded in their respective host-organisms: *Acasta* in sponges and *Mclellania* in *Mercenaria*.

The enigmas occur in three species of *Mercenaria* from as many geologic horizons. One specimen has been found in *Mercenaria cuneata* (Conrad) from the Choptank Miocene of Maryland and only one in *Mercenaria permagna* (Conrad) from the Croatan Pliocene from Lee Creek, North Carolina. All other specimens are from strata of Yorktown age from Virginia, North Carolina, and Florida. Inasmuch as the search failed to yield additional specimens in Croatan mercanarias, it is assumed that the numerous float specimens at Lee Creek came from the more or less leached beds of the Yorktown Formation; the enigmas being calcitic like ecphoras, oysters, pectens, and barnacles commonly found well preserved in these beds. In the Yorktown strata the engimas occur in *Mercenaria corrugata* (Lamarck) and in its "tridacnoides" variant. Since this species is the principal host of the enigmas and the name *corrugata* is used here in an American study for the first time, it is necessary to explain its resurrection.

Resurrection of *Mercenaria corrugata* (Lamarck).—Lamarck (1818:558) described two species of fossil bivalves, *Cyprina corrugata* and *Cyprina tridacnoides*, in that order (his Cyprines 4 and 5), both then thought to be from Italy. Under *C. tridacnoides*, Lamarck augmented his description by reference to a figure in Lister (1692, pl. 499: fig. 53). The name is so apt that it might have been possible to recognize the distinctive American fossil, presently known as *Mercenaria tridacnoides*, without the figure. These large heavy shells with conspicuous, broad undulations, otherwise totally unknown in the genus *Mercenaria*, are widely regarded as an "abnormal" or "pathological" form. They occur with the more common *Mercenaria rileyi* (Conrad, 1838), which is always regarded as the "normal" form. These two forms are undoubtedly closely related. Thus, the necessity of using the historically prior name of an "abnormal" variant as the name of the species has resulted occasionally in rather strained circumlocutions in order to avoid just that. Whereas Gardner's unrealistic arrangement (1943:130–133) is neither nomenclatorially nor genetically defensible, Dall (1903:1310–1311), followed by Palmer (1927:399), had earlier used *tridacnoides* as the specific name.

Favre (1914, pls. 16–19) in his illustrations of the type specimens of Lamarck's fossil invertebrates, figured both *Cyprina corrugata* and *Cyprina tridacnoides*. According to Favre the specimens of both had the original labels of Lamarck. *Cyprina tridacnoides* is represented by a monotype (holotype). The two specimens (syntypes) of *Cyprina corrugata* were recognized by Favre as American fossils and identified as *Venus mortoni* Conrad, 1837 (Favre, 1914, pl. 16: fig. 91) and *Venus rileyi* Conrad, 1838 (Favre, 1914, pl. 17: fig. 92). The specimen identified as *Venus mortoni* has "*Cyprine ridée*," Lamarck's 1818 vernacular for the species, written on the shell. The other specimen has "*Cyprina corrugata*" written on it, which shell also has the measurement given in the original description (Lamarck, 1818:558); thus it (Favre, 1914, pl. 17: fig. 92) is the obligatory lectotype of *Cyprina corrugata* Lamarck, here designated. Concomitant with this action, *Cyprina corrugata*, numerically prior, is given absolute priority over *Cyprina tridacnoides* in exercise of my right as first revisor. The name of the species formerly known as *Mercenaria tridacnoides rileyi* then must become *Mercenaria corrugata* (Lamarck). As a convenience the informal term *Mercenaria corrugata* "tridacnoides" is used for the statistically important, striking variant of *Mercenaria corrugata* (Lamarck), which appears to be the most common host of *Mclellania aenigma*. This is in conformity with the rule of the code of zoological nomenclature that variations cannot be formally recognized.

One further note on the nomenclature: until the question of the type-species of *Venus* was settled by the International Commission on Zoological Nomenclature (Opinion 195) in 1954, the genus here referred to as *Mercenaria* was more commonly known as *Venus*. It follows that the *Venus corrugata* of Gmelin 1790 has priority over the species in question only so long as the taxa concerned are referred to *Venus*; with the transfer

to *Mercenaria*, the rule of homonymy no longer applies.

ACKNOWLEDGMENTS.—The new genus is named for Jack McLellan in appreciation of his interest and support of the Lee Creek project. I am grateful to Blake Blackwelder, Cristina Silber, and Zalman Altshuler, all of the U.S. Geological Survey, for substantial contributions to this paper: Blackwelder for detecting the *sine qua non* specimen in the Lee Creek *Mercenaria* and its identification as *M. permagna* (Conrad), and recovery of the off-shore specimen of *Scalpellum magnum* and determination of its age; Silber for the X-ray diffraction analyses of an enigma and of the "cancerous panope"; Altshuler for pertinent discussions of the problem. I appreciate very much the courtesies extended to me by C. Allen Child of the Department of Invertebrate Zoology, National Museum of Natural History, Smithsonian Institution, and by Austin Williams of the National Marine Fisheries Service Systematics Laboratory, Department of Commerce. I thank Robert McKinney and Harry Mochizuki of the U.S. Geological Survey for the fine photographs and prints; and Lawrence B. Isham of the Department of Paleobiology, National Museum of Natural History, for the discriminating preparation of the plates. I especially appreciate and thank Barbara Bedette of the U.S. Geological Survey for editorial comment and the excellence of the typescript.

The cirriped section of the arthropod volumes of the *Treatise on Invertebrate Paleontology* has been an indispensable source for information pertinent to this study. I am greatly indebted to its authors, William A. Newman, Victor A. Zullo and T.H. Withers. Without their comprehensive compilation my task would have been insurmountable.

I have benefited at varous stages of this manuscript from reviews by friends and colleagues: Zalman Altshuler, Cristina Silber, Norman Sohl, and John Pojeta, U.S. Geological Survey; Frederick M. Bayer, Porter M. Kier, and Thomas Waller, National Museum of Natural History, Smithsonian Institution; Joseph Carter, Department of Geology, University of North Carolina; Jules R. DuBar, Department of Geology, Morehead State University; and Austin Williams, National Marine Fisheries Service Systematics Laboratory, Department of Commerce.

## Systematics

Class CIRRHIPEDIA Rafinesque, 1815
Order THORACICA Darwin, 1854
Suborder BALANOMORPHA Pilsbry, 1916
Family BALANIDAE Leach, 1817
Subfamily MCLELLANIINAE, new subfamily

Solid, calcitic basis, either single or aggregate of anastomosed individuals, embedded in fossil shells of the bivalve *Mercenaria*; embedment results from simultaneous growth of basis and host-*Mercenaria*. Hard parts of capitulum unknown; probably obsolete.

### Genus *Mclellania*, new genus

Type-species.—*Mclellania aenigma*, new species.

The description of the species serves for both genus and species inasmuch as the genus is monotypic.

### *Mclellania aenigma*, new species

PLATE 1: FIGURES 1–9; PLATES 2, 3

DESCRIPTION OF HOLOTYPE.—Small, solid, conical, layered, calcitic basis; in living position, apex down. Upper surface of basis slightly concave, xenomorphic, preserving the contour of the inner surface of the *Mercenaria*, which contains just under its umbo the locus from which the basis came; the basis fitting precisely in the concavity of the locus. Basal surface of a crystalline appearance. Layers rapidly expanding and alternately light and dark. Radial markings of the basal surface formed by minute indentations in the edge of each succeeding layer; markings not expanding in size but new indentations regularly intercalated, producing a uniform appearance from the initiation of the earliest markings to the latest.

Other fewer, heavier, radial indentations beginning at the apex become obsolete or shallow and account for the irregular sinuosity of the overall subcircular outline of the basis. With the apex up, each expanding layer producing a steplike appearance on a microscopic scale.

Description of Aggregate Paratypes.—Almost half of the paratypes are aggregates, specimens made up of two or more anastomosed individuals. Their basal surfaces show the initial areas of the individuals and their subsequent impingement upon each other, but their upper surfaces are so completely anastomosed that they appear to be one individual if seen from above. The aggregate paratypes are all larger than the holotype, and in most specimens the layers expand even more rapidly than in the smaller single individuals. The markings are the same as described for the holotype, but in its larger aspect, an aggregate is more like a topographic model in miniature (Plate 1: figure 7).

Discussion.—The definitive description is limited to the holotype, the only specimen once embedded in a *Mercenaria* that has not been forcibly removed. This is the specimen that dropped from the *Mercenaria* during washing (p. 483). It is unique in that the demarcation between the enigma and the host-*Mercenaria* is sharply defined. It is consequently more easily described than paratypes later removed from the mercenarias. These paratypes were firmly embedded in the shells, and none has been removed without difficulty and some damage to the enigma and the *Mercenaria* shell.

The form of the enigma basis is inherently functional; the details and form of the locus in the *Mercenaria* are responsive and the juxtaposition of the *Mclellania* basis with the *Mercenaria* produces xenomorphism in both. The upper surface of the enigma takes the form of the inner surface of the *Mercenaria*, and the shell surrounding the cavity of the locus preserves in minute detail the form and exterior sculpture of the basal surface of the *Mclellania*. Production of this isochronous xenomorphism requires simultaneous growth of both organisms.

Some *Mercenaria* shells contain two enigmas, sometimes two singles, sometimes mixed singles and aggregates, and one contains two aggregates. Some small specimens are so close to each other or to aggregates that they might have become aggregates or parts of other aggregates if growth had continued. A massive aggregate (Plate 2: figure 2) seems to have been formed of several anastomosing aggregates.

The enigmas are found embedded anywhere in the mercenarias above the pallial line, but the preferred position seems to have been in juxtaposition to the anterior adductor muscle of the left valve of the mercenarias (see p. 490). The significance of this preference has not been deduced. One float specimen (USNM 304381) (Plate 1: figure 8) appears to have lived high under the umbo of a *Mercenaria* in space so constricted that it curled back upon itself. The largest paratype (USNM 305107) and most important specimen, other than the holotype, is the massive aggregate which covers 90 percent of a left valve of *Mercenaria* above the pallial line. The normally expanding growth of the pallial sinus of the *Mercenaria* has overrun an edge of the enigma (Plate 2: figure 2). In cross-section (Plate 3) the calcitic layers of the enigma and the aragonitic layers of the *Mercenaria*, superficially, appear to be continuous. However, under magnification a dark layer shows a definite lag and few of the layers are precisely continuous. Both the enigma and the *Mercenaria*, ipso facto, are subject to the same environmental conditions. The lag may indicate that the enigma received its sustenance through the *Mercenaria*.

The enigmas did not fill cavities or depressions in the mercenarias, but they were produced layer by layer at the same rate, probably no more than one layer ahead of the layers of the *Mercenaria* shells. This would be sufficient to prevent the mercenarias from overrunning the enigmas. Some specimens and also a section (Plate 2: figure 2) indicate that the effort to overrun the enigmas may have been more or less constant. In the cross-section, the *Mercenaria* layers are seen to have impinged upon the initial stage of the enigma to

the extent that its width is very much reduced (Plate 3: figure 2). Some enigmas that have been removed from the mercenarias and some of the free-float specimens have white shell that appears to be the aragonitic layers of the mercenarias impinging upon, and caught between, the edges of the layers of the enigmas.

MEASUREMENTS.—The shapes of large specimens of *Mclelannia aenigma* are so ill-defined because of their various locations in the *Mercenaria* that measurements are not particularly meaningful. A few, including the figured aggregate paratype USNM 305107 (Plate 2: figure 2; Plate 3), encompass so much of, or are so spread out over the inner surface of, the shells that even surface measurements are not possible. Measurements of the holotype, the float paratypes, some paratypes that have been removed from their mercenarias, and some surface measurements of a few paratypes still in their mercenarias are given in Table 1.

TABLE 1.—Measurements (mm) of types of *Mclellania aenigma* (aggregate indicates two or more enigmas occur in one *Mercenaria* and have same catalog number; dash indicates measurement could not be taken because specimens are embedded)

| *USNM* | *Greatest diameter* | *Smallest diameter* | *Thickness* |
|---|---|---|---|
| HOLOTYPE | | | |
| 304378 (single) | 9.5 | 9.3 | 3.0 |
| PARATYPE | | | |
| 304379 (aggregate) | 39.2 | 34.7 | 8.7 |
| 304380 (aggregate) | 43.8 | 29.6 | 6.6 |
| 304381 (aggregate) | 26.4 | 20.4 | 5.3 |
| 304382 (single) | 11.8 | 10.3 | 2.7 |
| 304383 (aggregate) | 31.7 | 23.1 | 6.4 |
| 304384 (aggregate) | 43.2 | 26.6 | 4.3 |
| 304385 (single) | 21.8 | 19.6 | 5.2 |
| 305106 (aggregate) | 21.7 | 16.7 | 7.0 |
| 305108 (single) | 13.5 | 7.9 | |
| 305120 (aggregate) | 30.7 | 28.6 | 5.3 |
| (single) | 11.7 | 10.4 | – |
| 305121 (aggregate) | 23.7 | 15.3 | |
| (single) | 7.3 | 6.4 | |
| 305122 (aggregate) | 50.3 | 25.3 | 4.6 |
| 305125 (aggregate) | 21.3 | 19.3 | ~ 3.0 |

TYPES AND OCCURRENCES.—The specimens (primary types) of *Mclellania aenigma* have been found from Maryland to Florida with by far the greater number in Virginia and North Carolina. The following catalog of the types details the occurrences in the host-*Mercenaria* species and the localities. An "infected" *Mercenaria* and its enigma(s) have been given the same catalog number. USNM 304378 is the holotype; all others are paratypes.

USNM 304378 (single), in left valve of *Mercenaria permagna*: top 1.5 feet (0.46 m) of upper shell bed, north wall, Texasgulf Inc., Lee Creek Mine, south side of Pamlico River, near Aurora, Beaufort County, North Carolina; Croatan Formation (Plate 1: figures 1–4).

USNM 304379 (aggregate, Plate 1: figures 5–6), 304380 (aggregate, Plate 1: figure 7), 304381 (aggregate, Plate 1: figure 8), 304382 (single, Plate 1: figure 9), 304383 (aggregate), 304384 (aggregate); all float: Texasgulf Inc., Lee Creek Mine, south side of Pamlico River, near Aurora, Beaufort County, North Carolina; probably Yorktown Formation.

USNM 304385 (single), float: Snell Island fill (USGS 21900), dredged from Tampa Bay, Pinellas County, Florida; occurs with Yorktown assemblage.

USNM 305106 (aggregate), float: Texasgulf Inc., Lee Creek Mine, south side of Pamlico River, near Aurora, Beaufort County, North Carolina; probably Yorktown Formation.

USNM 305107 (aggregate), in left valve of *Mercenaria corrugata* "tridacnoides": 15 miles (24.14 km) above Bell's bridge, Tar River, Edgecombe County, North Carolina; Yorktown Formation (Plate 2: figure 2; Plate 3).

USNM 305108 (single), in right valve of *M. corrugata* "tridacnoides": 4 miles (6.44 km) northwest of Williamston, Martin County, North Carolina; Yorktown Formation (Plate 2: figure 1).

USNM 305109 (aggregate), 305110 (aggregates), in right valves of *Mercenaria corrugata*: ¾ mile (0.89 km) north of Grimesland, Pitt County, North Carolina; Yorktown Formation.

USNM 305111 (single), in left valve of *M. corrugata* "tridacnoides": Tar River, right bank of Boyd bridge about one mile (1.61 km) north of Grimesland, Pitt County, North Carolina (USGS 11835); Yorktown Formation.

USNM 305112 (single), in left valve of *M. corrugata*: Shiloh Mills, Edgecombe County, North Carolina; Yorktown Formation.

USNM 305113 (aggregate), in right valve of *M. corrugata*: 1½ miles (2.41 km) west of Greenville, Pitt County, North Carolina; Yorktown Formation.

USNM 305114 (two aggregates), in left valve of *M. corrugata*: 3 miles (4.83 km) southwest of Frog Level, Pitt

County, North Carolina; Yorktown Formation.

USNM 305115 (single), in left valve of *M. corrugata*: upper bed, Alum Bluff, Liberty County, Florida; Jackson Bluff Formation.

USNM 305116 (single), in left valve of *M. cuneata*: Choptank River, Caroline County, Maryland; Choptank Formation.

USNM 305117 (single), in left valve of pair of *M. corrugata* "tridacnoides": Bed C, Moore House, York River, York County, Virginia (USGS 24029); Yorktown Formation.

USNM 305118 (single), 305119 (single), in left valves of *M. corrugata* "tridacnoides": Lieutenant Run, Petersburg, Virginia; Yorktown Formation.

USNM 305120 (single and aggregate), in right valve of *Mercenaria* sp.: Sunken Marsh Creek, James River, Surry County, Virginia; Yorktown Formation.

USNM 305121 (single and aggregate), in left valve of *M. corrugata* "tridacnoides": Grove Wharf, Surry County, Virginia (USGS 2452); Yorktown Formation.

USNM 305122 (single and aggregate), in left valve of *M. corrugata* "tridacnoides": Lieutenant Run, Petersburg, Virginia; Yorktown Formation.

USNM 305123 (single and aggregate), in right valve of *M. corrugata*: Suffolk, Nansemond County, Virginia; Yorktown Formation.

USNM 305124 (two singles), in left valve of *M. corrugata* "tridacnoides": 2½ to 3 miles (4.02 to 4.83 km) below Seaboard Railway bridge, Sycamore, Southhampton County, Virginia; Yorktown Formation.

USNM 305125 (two singles), in right valve of *M. corrugata*: Sycamore, Southhampton County, Virginia; Yorktown Formation.

USNM 305126 (aggregates), in both valves of *Mercenaria* sp.: Yorktown, York County, Virginia; Yorktown Formation.

USNM 305127 (aggregate), in left valve of *M. corrugata*: Yorktown, York County, Virginia; Yorktown Formation,

USNM 305128 (single), in right valve of *Mercenaria* sp.: Yorktown, York County, Virginia; Yorktown Formation.

USNM 305129 (aggregate), in right valve of *M. corrugata*: Yorktown, York County, Virginia; Yorktown Formation.

USNM 305130 (single), in left valve of *M. corrugata* "tridacnoides": Yates cut, unit 3, College of William and Mary campus, Williamsburg, Virginia; Yorktown Formation.

USNM 305131 (single), in left valve of *M. corrugata* "tridacnoides": Golf course, Williamsburg, Virginia; Yorktown Formation.

Geologic Range.—The oldest occurrence of *Mclellania aenigma* is the single specimen from the Choptank Formation, Miocene, of Maryland; the youngest is the single specimen from the Croatan Formation, Pliocene, at Lee Creek. These two occurrences thus span the occurrence of the greater number of specimens from localities that fall in the Yorktown Formation or its equivalents. The age of some of these is based on the presence of the host-*Mercenaria* species *M. corrugata* "tridacnoides" here regarded as indicative of Yorktown age strata. All reports of occurrence of this variant outside these beds are based on single specimens of repaired broken valves. The Yorktown Formation, once the classic late Miocene of the Coastal Plain and based on faunal comparison with the European late Miocene, is regarded currently by micropaleontologists as Pliocene in age. The range then is Neogene; Neogene of the original definition, Miocene–Pliocene, i.e., late Tertiary.

An organism comparable to *Mclellania* may have existed in the Cretaceous. My colleague, Norman F. Sohl of the U.S. Geological Survey, has shown me his manuscript illustration of a depression of unknown origin in a Cretaceous oyster, which is reminiscent of the loci in mercenarias from which enigmas have been removed.

Data of Unknown Significance.—The hypodigm of *Mclellania aenigma* consists of the holotype and 40 paratypes, eight of which are free-float from the Lee Creek Mine and Florida. These eight specimens, six aggregates and two singles, contribute nothing to the data assembled here. These data are concerned with various aspects of the occurrence of the enigmas in the mercenarias. The other 33 paratypes occur embedded in 26 mercenarias from many localities. Unfortunately, only 2 of the 26 are complete: one (USNM 305126) has an aggregate enigma in each valve; the other (USNM 305117) is "infected" in only one valve, a single enigma in the left valve. Thus, the two complete mercenarias with the three enigmas, two in left valves and one in a right valve, exhibit the skew that is apparent in the remaining 24 "infected" unpaired valves. Of these, 9 are right valves and 15 are left valves. One of the components, 13 enigmas in 10 valves of *Mercenaria corrugata* "tridacnoides" has an even more pronounced skew toward left valves; 9 left

valves (with 12 enigmas) to one right valve (with one enigma). In contrast, the 13 enigmas in 11 valves of the nominate species, *M. corrugata*, are divided thus: 7 enigmas in 6 right valves to 6 in 5 left valves, an unremarkable proportion except in contrast to those in the "tridacnoides" variant. This suggests a relationship between the "tridacnoides" variant and left valves, a relationship which also extends to the enigmas embedded in juxtaposition to the anterior muscle scars of the mercenarias. This is the preferred locus of 13 out of 33 of the enigmas "infecting" the 26 mercenarias. In this case, the 13 enigmas occur in 13 valves, 9 of these valves are the variant and 4 are the nominate *M. corrugata*; 11 of the 13 are left valves and only 2 are right valves. We may be dealing with three interdependent variables: (1) the "tridacnoides" variant, (2) predisposition to left valves and (3) preference for juxtaposition to the anterior adductor muscle. In fact this combination is present in one of the two complete mercenarias. This specimen (USNM 305117), *M. corrugata* "tridacnoides," has an enigma in juxtaposition to the anterior adductor muscle scar of its left valve. It has been assumed that in the "populations" (thanatocoenoses) from which these specimens came that the numbers of right and left valves of these heavy shells are about equal. The equally (or more) important proportion of the variant "tridacnoides" (10 in the present collection) to the nominate species (11 in the collection), however, cannot be assumed. These data, based for the most part on unpaired valves, are interesting, but their significance is elusive, and they may or may not be validated by future collections containing many more complete specimens. Up to now, no mercenarias have been collected for the enigmas; their collection has been fortuitous.

If *Mclellania* eventually is discovered living, its soft anatomy. living habits, and life cycle may help explain these data and give answers to other interesting, and as yet unanswered, questions, such as the nature of the relationship of the individuals that make up the aggregates, how and at what stage the enigma enters the *Mercenaria*, and whether the enigmas have plates at an early stage.

## Discussion of Relationships of *Mclellania*

I have described *Mclellania aenigma* as a balanid cirriped and because of its peculiar or perhaps even unique habitat and evolutionary development, I have erected a subfamily for it. As pointed out, the most convincing evidence is the striking similarity of enigmas and the bases of species of *Acasta* (Family Balanidae); supported by their obvious morphologic and functional equivalence. There is also other, if less striking, evidence. To recapitulate and elaborate:

1. The mode of growth of enigmas and of other balanid barnacle bases is the same, although the final forms are markedly, but superficially, different. Probably in response to their loci, both are irregular in growth and consequently difficult to describe. They are formed of succeeding, expanding layers; in enigmas these are subplanar and in balanids planar to cup-shaped. Each develops characteristically: the enigmas become subconical bodies, and the bases of some species of barnacles become cup-shaped or planar bodies at right angles to the rest of the barnacle shell. In the enigmas, each succeeding layer expands during growth with its edge slightly curved upward to conform to the concave inner surface of its host. In comparison, some balanid bases are ideally described as growing and adhering to a flat surface, the edges of each succeeding, expanding layer curving downward over the preceding layer to afford firm attachment. The radial markings of the enigmas are comparable to markings on some balanomorph bases, which result from their interlocking contact with the compartmental plates of their shell walls. The stronger radials account for the sinuosity of the subcircular outline of enigmas, which is comparable to the rudely hexagonal outline of the basis of *Acasta cyathus*, relict from its six compartmental plates. This suggests that *Mclellania* may have had plates at an early stage of its growth.

2. Enigmas and the shells of thoracican cirripeds are both composed of calcite. According to Newman, Zullo, and Withers (1969:218), barnacle shells are predominantly calcite and contain no aragonite. Perhaps the report (Lowenstam, 1964:385) of aragonitic bases in the balanomorphs, *Catophragmus* and *Tetraclita*, is best regarded in the balance as no more than the ubiquitous exception.

3. Alternate light and dark layers are common to enigmas and thoracicans. In enigmas and in balanid bases, the alternate layers are prominent when exposed. Other thoracican lepadomorphs, such as *Scalpellum magnum* Darwin (1851, pl. 1: fig. 1e; see also Withers, 1953, pl. 52, fig. 7), show the alternation on the exterior. The specimen illustrated here (Plate 1: figure 10) was recovered by Blake Blackwelder from off-shore dredgings in the Atlantic Ocean, where it was associated with Yorktown age fossils. Withers (1953:302) does not report the species outside the Pliocene Coralline Crag of England.

4. The aggregates may have a function homologous to that of crowded groups of barnacles, in which larger specimens adhere to each other and sometimes overrun smaller specimens. Barnacles, according to Schäfer (1972:114), live crowded, not because of advantages of environment, but because cirripeds, although sessile, have retained internal fertilization and must be within reach of each other. The aggregate enigmas are anastomosed, but crowded barnacles, though tightly adherent, are not and cannot be anastomosed, because of the growth requirements of the compartmental plates of their shell walls. Inasmuch as there could hardly be an environmental advantage from closeness within the mercenarias, by extrapolation, it is assumed that sexuality is the compulsion. Fourteen (over 41%) of the 34 enigma specimens in mercenarias are aggregates; most of the single specimens are small to very small (Table 1), presumably not mature. The aggregates are all larger than the singles, not just because they are made up of more than one individual, but also because the individuals that make up the aggregates tend to be larger. The aggregates may be the sexually mature, adult condition.

Obviously, *Mclellania* lived between the mantle and the shell of a bivalve. This it has in common with *Malacolepas* Hiro (1933:233–239), a lepadomorph cirriped described as living in and attached to shells of two genera of living bivalves, *Cucullea* and *Venerupis*, in Japanese waters. Of necessity, *Mclellania* and *Malacolepas* are homologous in the area of attachment; Newman, Zullo, and Withers (1969:217) have pointed out Darwin's determination of the homology of Lepadomorpha and Balanomorpha in this respect. It is difficult to assess from Hiro's description, but the homology may extend even further in the case of *Mclellania* and *Malacolepas*. In part, the specimens of *Malacolepas* are surrounded by calcareous tubes believed by Hiro to have been produced by the bivalves. His reasons are not particularly convincing in light of the two specimens of *Malacolepas* in *Venerupis* which "have a common cup around the basal parts" (Hiro, 1933:238). A consideration of possible homology with the *Mclellania* aggregates is inescapable, but without specimens I cannot go further. At least one other condition may be had in common: *Malacolepas* has no plates, a condition not uncommon in Lepadomorpha, but one, apparently, unknown in Balanomorpha. *Mclellania*, at some point in its existence (evolution or growth), must have had plates. No other explanation seems possible for the radial markings on the enigmas. Either the plates were lost at an early stage of growth or the soft parts were predisposed to replicate relict conditions in forming the hard parts of the enigmas. The fact remains that the aggregates could not have had plates. They were lost at some point in the evolution or during the growth of the enigmas within the protected environment of the *Mercenaria* interior.

This parallelism between forms in Balanomorpha and in Lepadomorpha is interesting, particularly so because of the possibility of parasitism in both. Parasitism is not rare in lepadomorphs, but I have not seen it recorded in balanomorphs. *Malacolepas* is said to be commensal (Hiro,

1933:233). Both *Malacolepas* and *Mclellania*, living in the restrictive niche between the mantle and the shell of bivalves, must somehow be sustained by their hosts. In neither case can a positive benefit from the association be deduced, and the association is not certainly, demonstrably harmful. As recounted earlier, however, some evidence indicates that there may have been a constant effort by the mercenarias to overrun the enigmas. Empirically, I believe *Mclellania* to have been a parasite. *Mercenaria* has survived and *Mclellania* is extinct, but for a time this balanomorph evolved and produced a survival platform within *Mercenaria*.

In my limited acquaintance with arthropod literature I have not seen an account of anastomosed individuals, or aggregates. Within the Thoracica, a highly evolved sessile group of great diversity presumably descended from free-living progenitors, anastomosed individuals may represent a trend or possibly nothing more than plateless proximity.

The complexity and diversity of form and habitat of the Cirrhipedia, as noted by the specialists, is impressive, but the aggregate specimens of *Mclellania* may be unique and add yet another component to the diversity of the class.

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## PLATE 1

*Mclellania aenigma*, new genus, new species

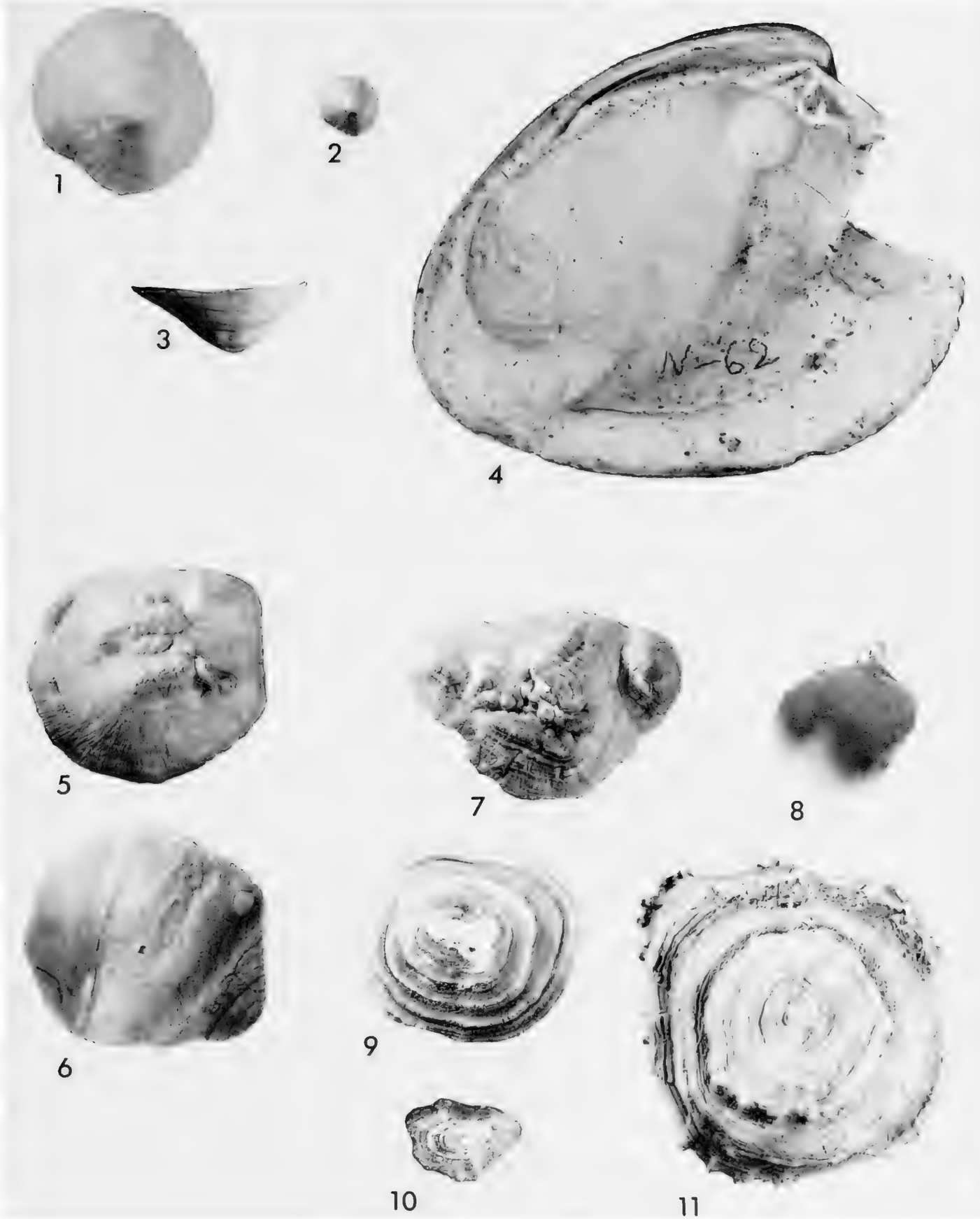
1–3. Holotype USNM 304378; 1, basal view, × 3; 2, basal view, × 1; 3, side view, × 3.
4. Locus of holotype (the light circular depression under the umbo) in shell of *Mercenaria permagna*, × 1.
5, 6. Aggregate paratype USNM 304379; 5, basal view, and 6, upper surface, showing xenomorphic markings derived from inner surface of a *Mercenaria*, × 1.
7. Aggregate paratype USNM 304380, basal view, × 1.
8. Aggregate paratype USNM 304381 from high under the umbo of a *Mercenaria*, upper surface, × 1.
9. Paratype USNM 304382; highly weathered basal surface showing light and dark layers, × 3.

*Scalpellum magnum* Darwin

10. Upper latus, USNM 304386, of fossil from off-shore dredging in the Atlantic Ocean, × 3.

*Acasta cyathus* Darwin

11. Basal view of USNM 7842 figured by Pilsbry (1916, pl. 57: figs. 1, 1a–b) showing basis and interlocking edges of capitulum, ~ × 10.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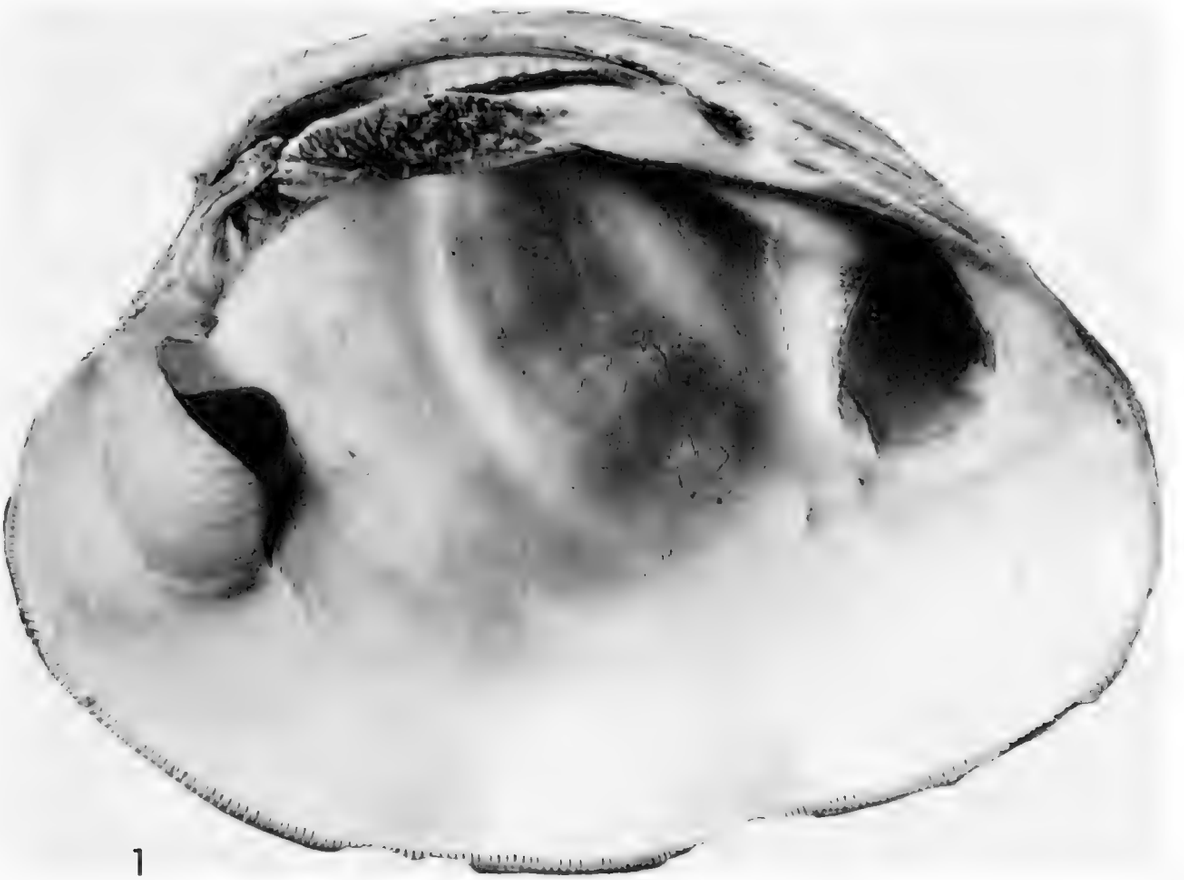
## PLATE 2

*Mclellania aenigma*, new genus, new species

1. Paratype USNM 305108 embedded in juxtaposition to anterior adductor muscle scar in right valve of *Mercenaria corrugata* "tridacnoides" from 4 miles (6.4 km) northwest of Williamston, North Carolina, × 1.
2. Aggregate paratype USNM 305107 embedded in and covering greater part of inner surface of left valve of *M. corrugata* "tridacnoides" from 15 miles (24 km) above Bell's bridge, Tar River, North Carolina; showing position of cross-section, × 1.



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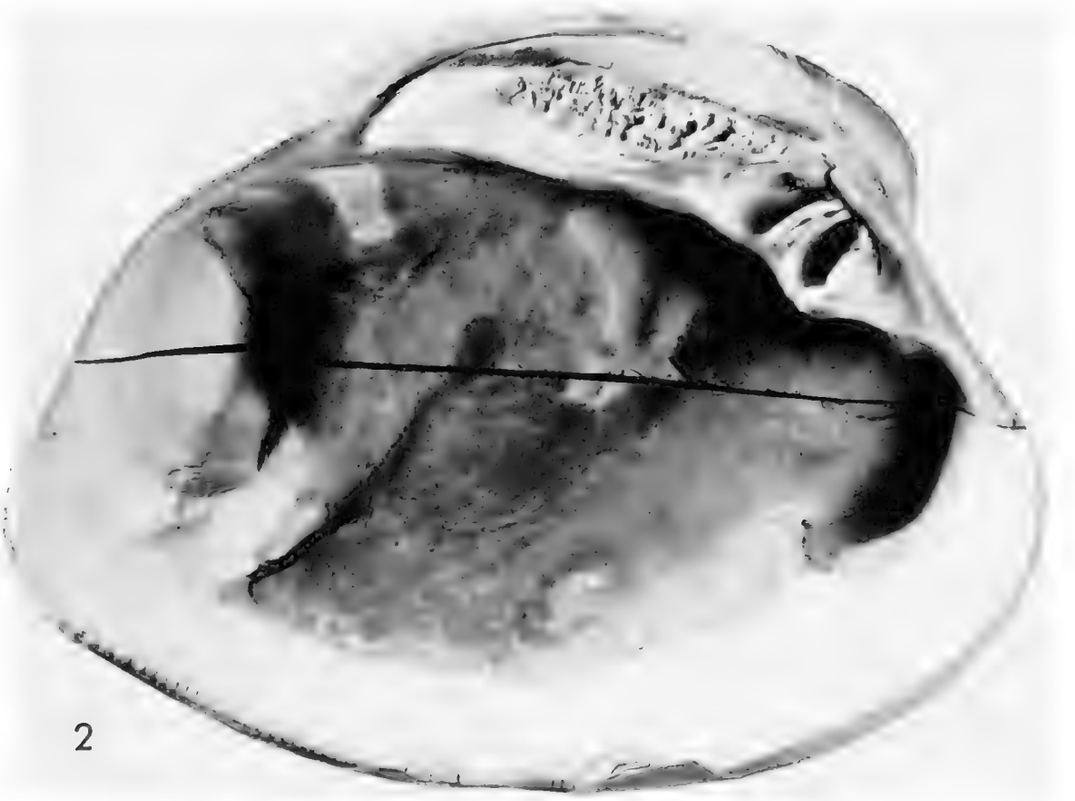

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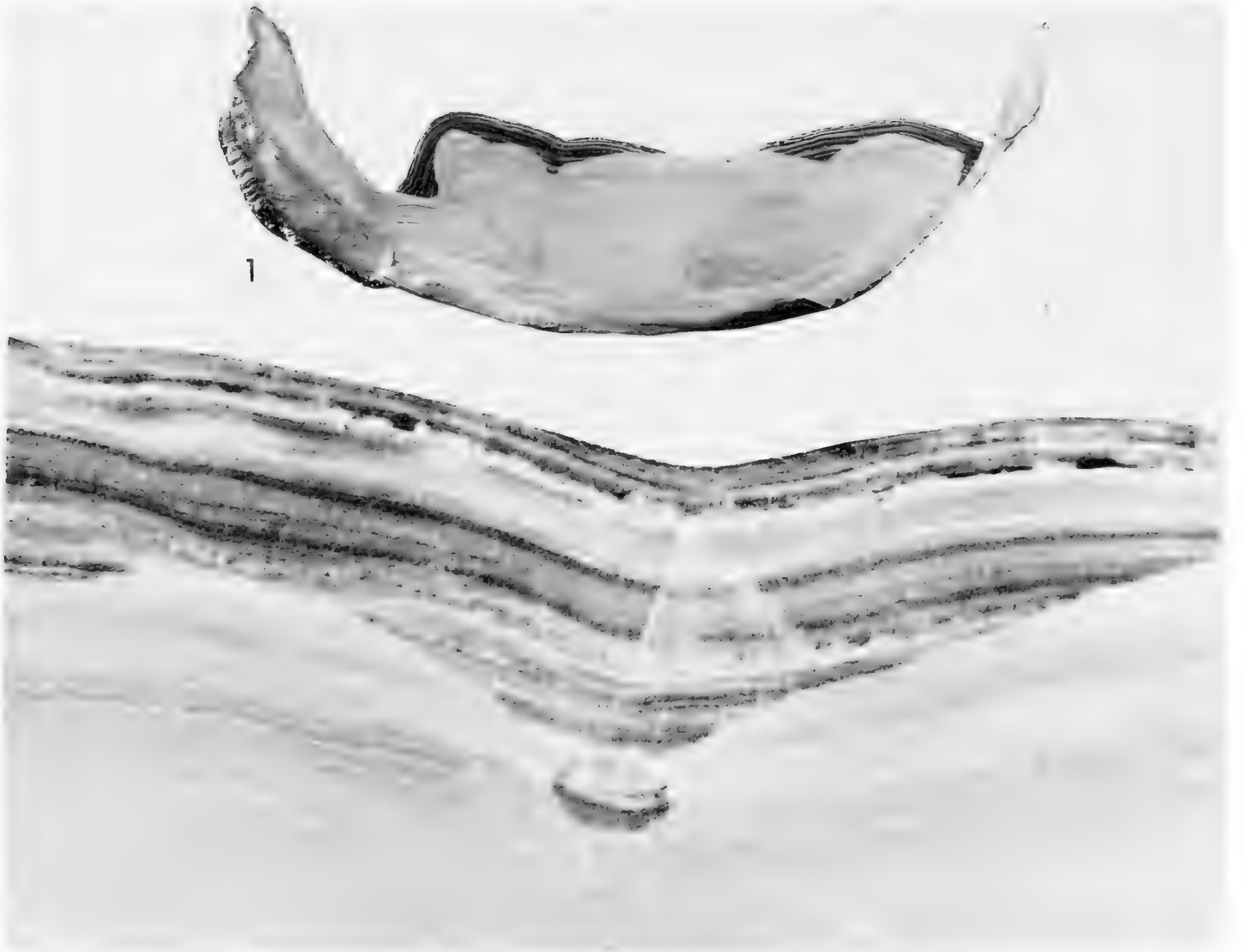


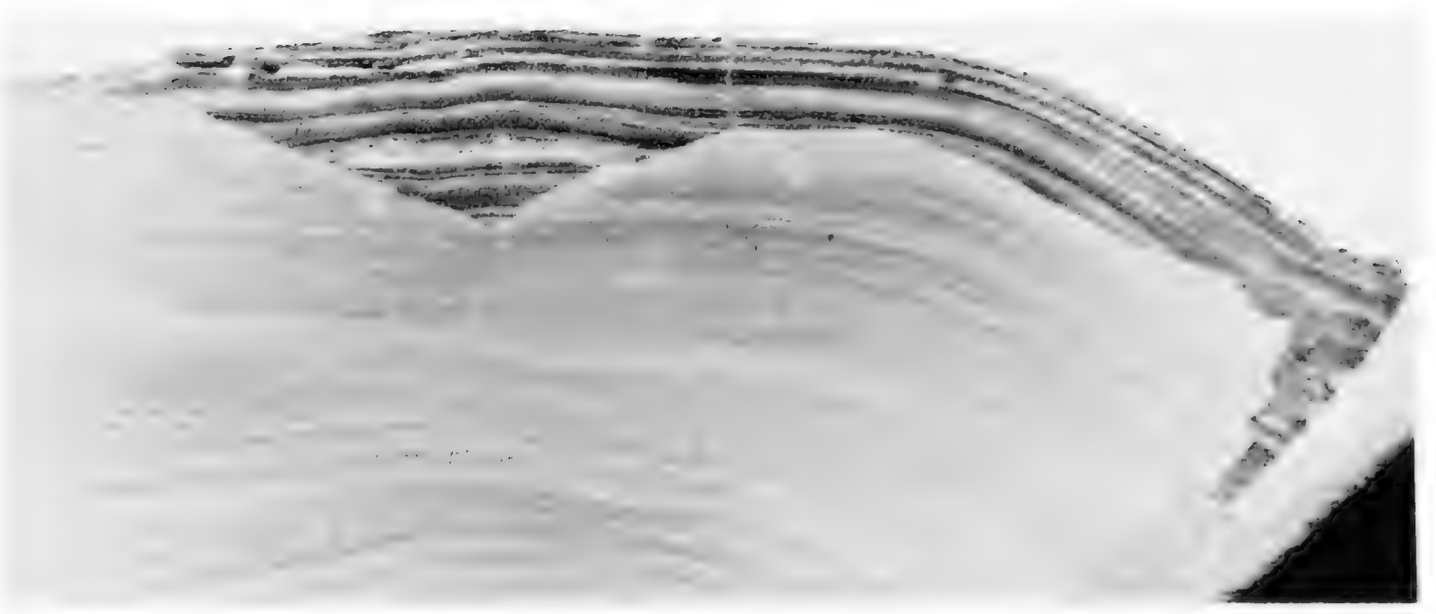


**PLATE 3**

*Mclellania aenigma*, new genus, new species

1–3. Aggregate paratype USNM 305107 embedded in left valve of *Mercenaria corrugata* "tridacnoides"; 1, cross-section at level of adductor muscle scars, × 1; 2, posterior portion of cross-section, × 5; 3, anterior portion of cross-section, × 5.

# Upper Cenozoic Echinoids from the Lee Creek Mine

*Porter M. Kier*

ABSTRACT

One Miocene, three Pliocene, and two Pliocene-Pleistocene echinoid species have been collected from the Lee Creek Mine, Aurora, North Carolina: *Abertella aberta* (Conrad) from the middle Miocene Pungo River Formation; *Echinocardium kelloggi*, new species, *Psammechinus philanthropus* (Conrad), and *Arbacia improcera* (Conrad) from the lower part of the Yorktown Formation (lower Pliocene), and *Mellita* cf. *M. aclinensis* Kier and *A. improcera* (Conrad) from the Croatan Formation (Pliocene-Pleistocene).

## Introduction

Only a few specimens representing five species of echinoids have been collected at the Lee Creek Mine and most of them were found by Mr. Jack H. McLellan, who most generously presented them to the National Museum of Natural History, Smithsonian Institution. The mine is located on the south side of the Pamlico River, near Aurora, Beaufort County, North Carolina, and is operated by Texasgulf Inc. The stratigraphy, age determinations of the beds, and geographic setting of the mine are described in detail by Gibson (pp. 57–77, herein) and Hazel (pp. 90–98, herein).

*Abertella aberta* (Conrad) is found in the upper limey beds of the middle Miocene Pungo River Formation. This species is previously known from the Choptank Formation in Maryland, which is considered to be middle Miocene. According to Gibson (1967:636–637) the Pungo River Formation correlates with the Calvert Formation of Maryland, which underlies the Choptank. *Echinocardium kelloggi*, new species, *Psammechinus philanthropus* (Conrad), and *Arbacia improcera* (Conrad) occur in spoil from the Yorktown Formation in beds which Gibson (1967) assigned to his unit 2, which he then considered late Miocene but now (p. 363, herein) places in the Pliocene. *Psammechinus philanthropus* and *A. improcera* have been found in Virginia in the Yorktown Formation (*Orionina vaughani* zone), which is now considered by Hazel (p. 94, herein) to be Pliocene. The beds where these specimens were found in the Lee Creek Mine are composed predominantly of spines that appear to be of *Echinocardium kelloggi*, suggesting that this species occurred in great numbers. *Mellita* cf. *M. aclinensis* Kier and fragments of *A. improcera* occur higher in the Croatan Formation, which Hazel (p. 94, herein) considers Pliocene-Pleistocene. *Mellita aclinensis* is known elsewhere from the Yorktown Formation (*Orionina vaughani* zone) of Virginia, the Tamiami Formation (also considered Pliocene by Hazel, p. 94 herein) of Florida, and the Yorktown Formation (*Puriana mesacostalis* zone) of North Carolina, which Hazel considers equivalent in age to the Croatan Formation.

ACKNOWLEDGMENTS.—I thank Jack H. McLellan, Peter J. Harmatuk, and the many other collectors who searched so assiduously for echinoids at the Lee Creek Mine and who then so generously presented them to the National Museum of Natural History. I am particularly in-

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debted to Clayton E. Ray who not only found some of the specimens but who has so ardently worked to bring about this comprehensive study of the fauna of the Lee Creek Mine. Thomas G. Gibson and Joseph E. Hazel advised on the stratigraphy and age determinations of the beds. The photography was done by Thomas F. Phelan and Mary H. Lawson.

### *Echinocardium kelloggi*, new species

FIGURE 1; PLATE 1: FIGURES 1–5.

Diagnosis.—Species characterized by high test, with wide area circumscribed by internal fasciole, oblique posterior truncation with entire periproct exposed adapically, and presence of large pore-pairs within internal fasciole in anterior poriferous zone of anterior petals.

MATERIAL.—One complete and uncrushed specimen, and many fragments.

SHAPE AND SIZE.—Specimen 36 mm long, 31.2 mm wide, 22.2 mm high; width 87 percent length, height 61 percent length. Greatest width anterior of center, greatest height midway between apical system and anterior margin; posterior pointed; truncation tilted exposing periproct adapically.

APICAL SYSTEM.—Four genital pores, ethmolytic with genital 2 extending far posteriorly, apical system located at distance from anterior margin to center of genital pores equal to 44 percent length of test.

AMBULACRA.—Anterior ambulacrum not petaloid, in groove from apical system to peristome, at anterior margin depth of groove equal to 4.4 percent length of test; pore-pairs within internal fasciole oblique with adapical pore of pair larger than adoral, small node between pores of each pair; pores in plates between internal fasciole and phyllode very small, single or slit-like; 8 pores in single poriferous zone from internal fasciole to peristome.

Anterior paired petals very wide with large pore-pairs outside of internal fasciole and 6 large pore-pairs within internal fasciole in posterior poriferous zones, 2 in anterior poriferous zones; petals slightly depressed, narrowing distally; 10 large pore-pairs outside of internal fasciole in petal IIa, 6 large pore-pairs outside of internal fasciole in petal IIb.

Posterior paired petals with no large pore-pairs within internal fasciole, 8 large pore-pairs in petal Va and petal Vb outside of internal fasciole; outer poriferous zones of anterior and posterior petals forming almost continuous arc; ambulacral plates beyond petals with single pores except within anal fasciole, where 2 pore-pairs in each single poriferous zone.

INTERAMBULACRA.—23 plates in interambulacrum 5, 14 in interambulacrum 1, 11 in 2 from internal fasciole to peristome.

PERISTOME.—Located at distance from anterior margin to anterior edge of peristome equal to 31 percent length of test; opening wider than high with width 20 percent length of test.

PERIPROCT.—Located high on posterior truncation, opening slightly higher than wide with height 14 percent length of test; located between plates 6–11.

ORAL PLATE ARRANGEMENT.—Labrum wide (Figure 1), extending across almost entire width of peristome, extending posteriorly and including part of second ambulacral plate; length of labrum, 11 percent length of test; plastron extending to posterior margin, length 50 percent length of test, greatest width 26 percent length of test; first plate of interambulacra 1, 4 very narrow. Ambulacra widening near peristome, phyllodes with 5 pores in ambulacrum III, 9 in II, 7 in I.

FASCIOLES.—Internal fasciole prominent, but tract not clear enough for measurement of width, fasciole crossing ambulacral plates 7a and 7b in ambulacrum III, 18a and 14b in ambulacrum II,

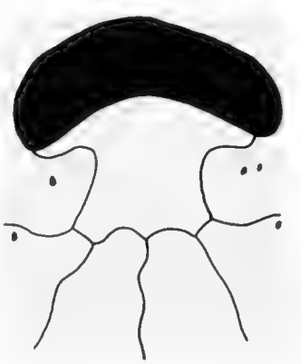

FIGURE 1.—*Echinocardium kelloggi*, new species, labrum of holotype, USNM 186521, × 4.

20a and 21b in ambulacrum I, 13a and 13b in interambulacrum 5, 10a and 10b in interambulacrum 1, 7a and 7b in interambulacrum 2; greatest width of area circumscribed by internal fasciole anterior of apical system, width 46 percent length of test. Tract of subanal fasciole not clear.

COMPARISON WITH OTHER SPECIES.—*Echinocardium kelloggi* is easily distinguished from the other two fossil species (Table 1) of this genus known from North America: *E. marylandiense* Kier and *E. orthonotum* (Conrad). It differs from *E. marylandiense* in having a narrower test with its width only 87 percent of its length whereas in *E. marylandiense* the width is 98 percent of the length. Its peristome is narrower, 19 percent its length versus 23 percent, its plastron is narrower 26 percent its length versus 35 percent, and the area circumscribed by the internal fasciole is wider in *E. kelloggi*, 46 percent the length of the test versus 39 percent in *E. marylandiense*. Furthermore, in *E. kelloggi* the test has its greatest height anterior to the apical system, whereas it is posterior in *E. marylandiense*, the posterior is very pointed in *E. kelloggi* and truncated in *E. marylandiense*, the internal fasciole extends further anteriorly, and the labrum extends back to the second ambulacral plate whereas in *E. marylandiense* it does not extend beyond the first plate, and in *E. kelloggi* there are two large pore-pairs in the anterior poriferous zone inside the internal fasciole, whereas there are no large pore-pairs in these zones in *E. marylandiense.*

*Echinocardium kelloggi* differs from *E. orthonotum* in its higher test with its height 61 percent the length versus 53 percent in *E. orthonotum*, shorter plastron, 52 percent the length as opposed to 57 percent, longer labrum, 11 percent the length versus 7 percent, and far wider area circumscribed by the internal fasciole, 46 percent the length versus 31 percent in *E. orthonotum. E. kelloggi* has two large pore-pairs within the internal fasciole in the anterior poriferous zone of the anterior petals, whereas there are none in *E. orthonotum*, its greatest height is anterior of the apical system, whereas it is posterior in *E. orthonotum*, and the posterior truncation is very oblique in *E. kelloggi* exposing all the periproct adapically, whereas it is more vertical in *E. orthonotum.*

TABLE 1.—Comparison of mean percent of test length among *Echinocardium kelloggi*, *E. orthonotum*, and *E. marylandiense*

| Characters measured | *E. kelloggi* | *E. orthonotum* | *E. marylandiense* |
|---|---|---|---|
| Width of test | 87 | 86 | 98 |
| Height of test | 61 | 53 | 59 |
| Distance from anterior edge of peristome to anterior margin | 31 | 27 | 32 |
| Width of peristome | 19 | 20 | 23 |
| Width of periproct | 14 | 16 | 13 |
| Length of plastron | 52 | 57 | 52 |
| Width of plastron | 26 | 29 | 35 |
| Length of labrum | 11 | 7 | 9 |
| Width of area circumscribed by internal fasciole | 46 | 31 | 39 |

OCCURRENCE.—Unit 2 (Gibson, 1967) of the Yorktown Formation (lower Pliocene). This echinoid, and many fragments of the same species, occurs in a lightly cemented greenish sand containing numerous hollow spines that appear to be from this species, and the mollusks *Ecphora quadricostata*, varieties of *Pecten jeffersonius*, and *Ostrea disparilis* (McLellan, 1972 in litt.). The echinoids appear to have been reworked; the tests are fragmentary, and the spines are jumbled.

TYPE SPECIMEN.—Holotype, USNM 186521. Collected by Jack H. McLellan. Fragments of other specimens collected by Clayton E. Ray.

### *Arabacia improcera* (Conrad)

PLATE 1: FIGURE 6

*Echinus improcerus* Conrad, 1843a:310.

*Psammechinus improcerus.*—Stefanini, 1912:705.

*Coelopleurus improcerus.*—Clark and Twitchell, 1915:180, pl. 84, fig. 4a–c.

*Arbacia improcera.*—Cooke, 1941:11, pl. 1, figs. 7–9.—Cooke, 1959:20, pl. 4, figs. 1–3.—Kier, 1963, pl. 1, fig. 6; 1972:8–9, pl. 1.

Five specimens belong to this species previously known from the lower Pliocene, Yorktown Formation (*Orionina vaughani* zone) in Virginia. These

specimens were collected in float but the matrix inside one of them contains hollow spines similar to those found in Gibson's (1967) unit 2 low in the Yorktown Formation, and presumably these specimens came from this unit. The spines are probably from *Echinocardium kelloggi*, new species.

Some isolated plates and spines that appear to belong to *A. improcera* were collected from higher in the Croatan Formation. Three interambulacral plates are preserved intact, and they have the same ornamentation of crenulations and a single row of tubercles typical of *A. improcera*. The spines are indistinguishable from those found in a living *Arbacia* (they have not been found previously with *A. improcera*) and some of the spines even retain their color, which is similar to the color of the spines of the Recent *Arbacia punctulata* (Lamarck), a species very similar to *A. improcera*, living off the coast of North Carolina.

Occurrence.—Complete specimens found in float of the Yorktown Formation (probably Gibson's unit 2). Fragments and spines found in the Croatan Formation.

Figured Specimen.—USNM 186522, collected by Robert W. Purdy. Other specimens collected by Clayton E. Ray, Jack H. McLellan, Donald and Ralph Chamness, and Edgar A. Womble, Jr.

### *Psammechinus philanthropus* (Conrad)

Plate 1: figure 7; Plate 2: figures 4–7

*Echinus philanthropus* Conrad, 1843a:310; Conrad, 1846:220.
*Psammechinus philanthropus.*—Meek, 1864:2.—Stefanini, 1912:705.—Clarke and Twitchell, 1915:181, pl. 84: fig. 6a–c.—Cooke, 1941:16; 1959:6, pl. 3: figs. 1, 2.—Kier, 1972:9–11, fig. 3, pl. 2: figs. 2–8, pl. 3, pl. 4: figs. 1, 3, pl. 5: figs. 1, 3.
*Echinus ruffini* Forbes *in* Lyell, 1845a:426, fig. 1a–d; 1845b: 560, 2 figs.).—Desor, 1858:121.—Emmons, 1858:306, fig. 239a–d.—Stefanini, 1912:705.

Fourteen specimens have been found that are indistinguishable from specimens of this species known previously from the Yorktown Formation (*Orionina vaughani* zone) of Virginia.

Occurrence.—Unit 2 (Gibson, 1967) of the lower Pliocene Yorktown Formation.

Figured Specimen.—USNM 186523. Collected by Jack H. McLellan. Other specimens collected by Francis M. Hueber, Michael Cohen, Edgar A. Womble, Jr., James Kaltenbach, Clayton E. Ray, Ralph Eshelman, Ronald H. Pine, and Frank C. Whitmore, Jr.

### *Abertella aberti* (Conrad)

*Scutella aberti* Conrad, 1842:194 [for a complete synonymy, see Cooke, 1959:44].

Many fragments can be assigned to this species previously known from the Miocene Choptank Formation in Maryland and the Chipola Formation in Florida.

Occurrence.—Upper limey layers of the middle Miocene Pungo River Formation, which Gibson (1967) correlates with the Calvert Formation of Maryland. Specimens collected by Jack H. McLellan.

### *Mellita* cf. *M. aclinensis* Kier

Plate 2: figures 1–3

*Mellita aclinensis* Kier, 1963:40–45, figs. 36–41; pl. 15:figs. 1–3; 1972:11–12, pl. 6, pl. 7: fig. 1.

There are five moderately well-preserved specimens that are very similar to this species previously described from the Pliocene Tamiami Formation in Florida, the Pliocene *Orionina vaughani* zone of the Yorktown Formation of Virginia, and the Pliocene-Pleistocene *Puriana mesacostalis* zone of the Croatan Formation of North Carolina. These specimens are also quite similar to *Mellita caroliniana* (Ravenel) known from Pliocene-Pleistocene beds in South Carolina. They appear to be intermediate between these two species. *Mellita aclinensis* is distinguished from *M. caroliniana* in having a flatter test and narrower lunules. These Lee Creek specimens have the flat test of *M. aclinensis* but in some of the Lee Creek specimens the lunules are more rounded as in *M. caroliniana.* Furthermore, in *M. aclinensis* the posterior lunule extends anteriorly almost in contact with the

periproct; whereas, in the Lee Creek specimens and in *M. caroliniana* the periproct is separated by a considerable distance from this lunule. Perhaps these two species are synonymous, but more specimens are needed before this can be decided.

OCCURRENCE.—Croatan Formation.

FIGURED SPECIMEN.—USNM 186524, collected by Jack H. McLellan; other specimens collected by Lauck W. Ward, William W. Bennett, and Clayton E. Ray.

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## PLATE 1

1–5. *Echinocardium kelloggi,* new species, USNM 186521, holotype: 1, adapical view; 2, adoral view; 3, right side; 4, posterior view; 5, anterior view; × 2. Unit 2 (Gibson, 1967) of the Yorktown Formation (lower Pliocene). Collector: Jack H. McLellan.

6. *Arbacia improcera* (Conrad), USNM 186522, adapical view, × 3. Presumably unit 2 (Gibson, 1967) of Yorktown Formation (lower Pliocene). Collector: Robert W. Purdy.

7. *Psammechinus philanthropus* (Conrad), USNM 186523, view of interambulacrum at ambitus, × 5. Unit 2 (Gibson, 1967) of the Yorktown Formation (lower Pliocene). Collector: Jack H. McLellan.

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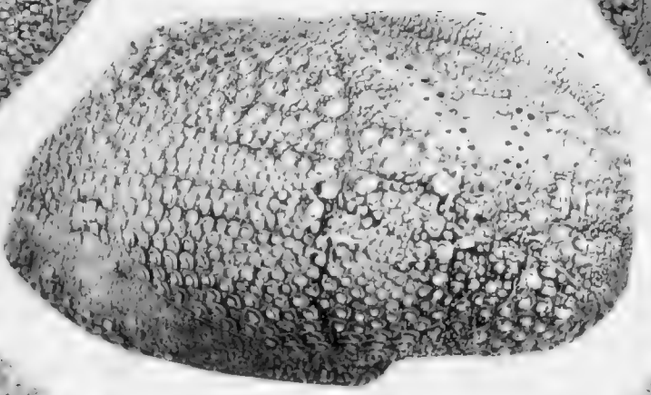

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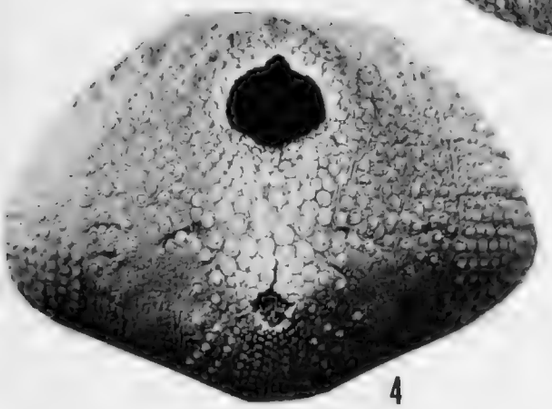

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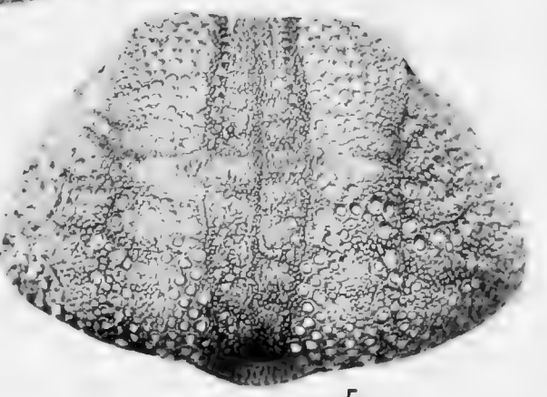

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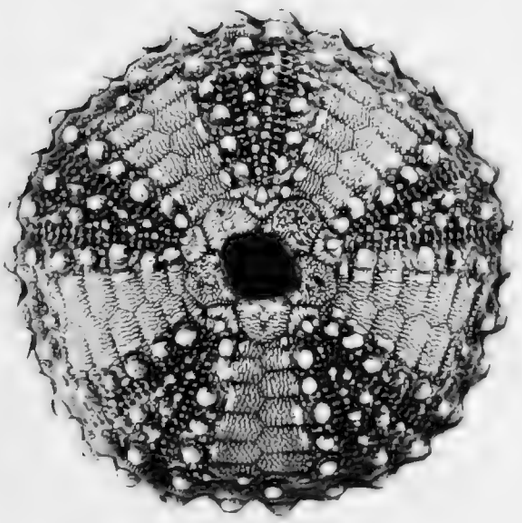

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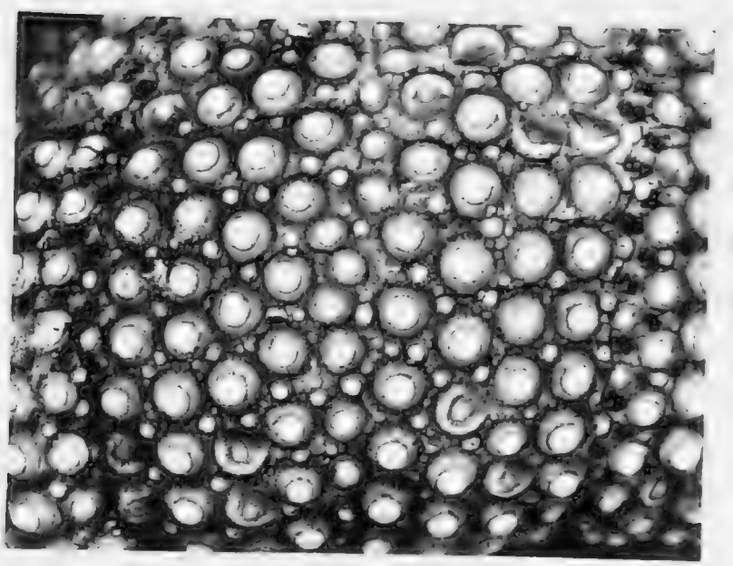

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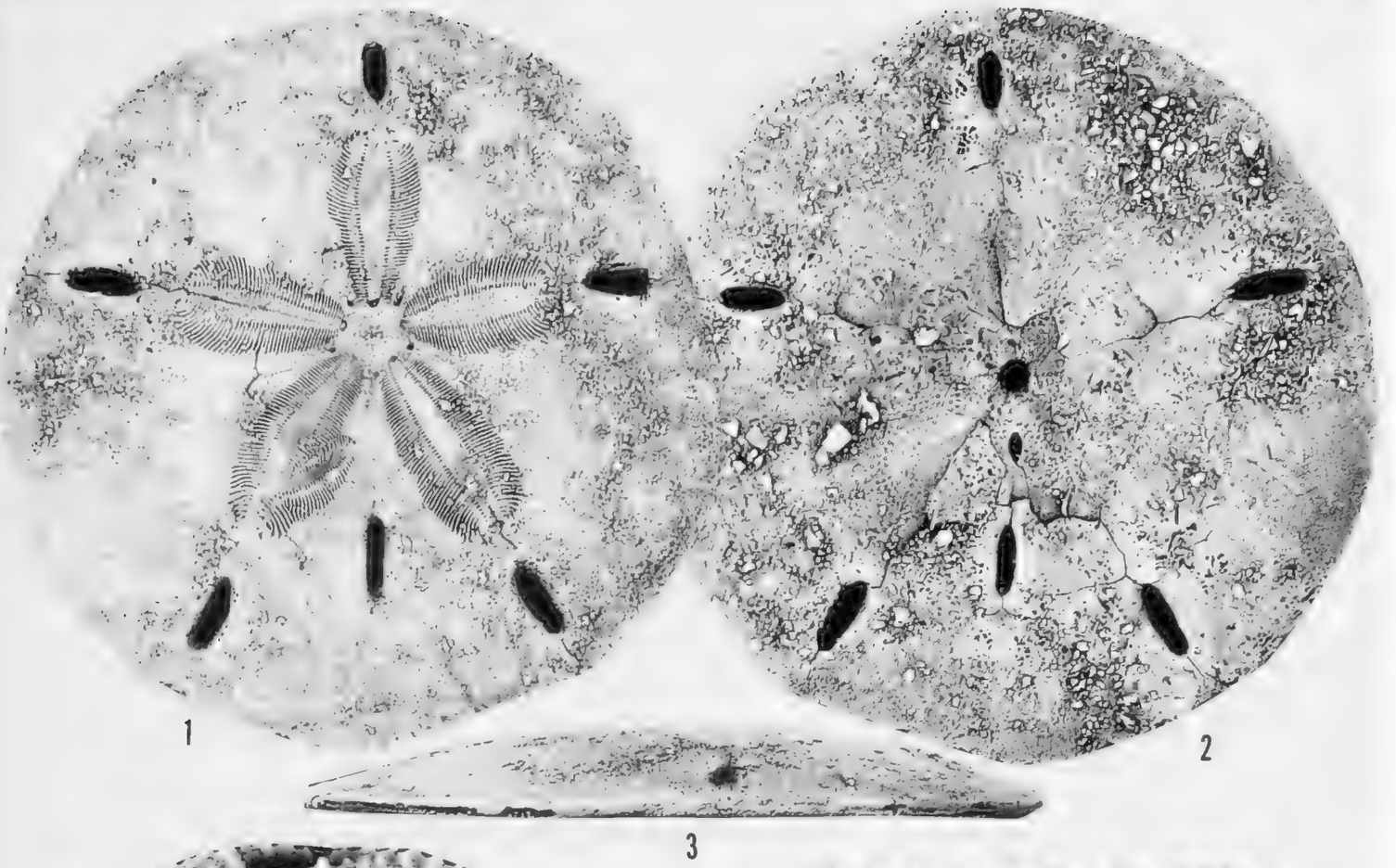
## PLATE 2

1–3. *Mellita* cf. *M. aclinensis* Kier, USNM 186524: 1, adapical view; 2, adoral view; 3, right side; × 2. Croatan Formation. Collector: Jack H. McLellan.

4–7. *Psammechinus philanthropus* (Conrad), USNM 186523: 4, side view; × 2; 5, adapical view, × 2; 6, adoral view, × 2; 7, view of ambulacrum at ambitus, × 5 (see Plate 1: figure 7 for view of interambulacrum). Unit 2 (Gibson, 1967) of the Yorktown Formation (lower Pliocene). Collector: Jack H. McLellan.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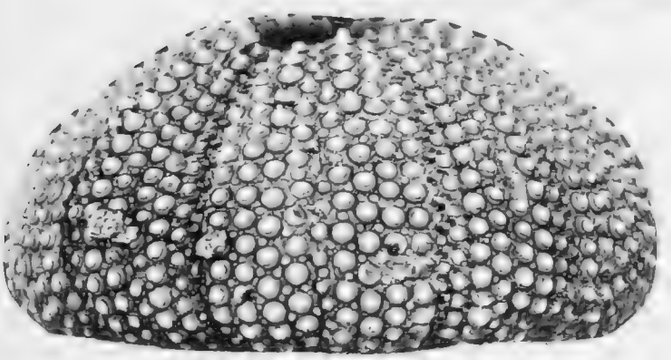
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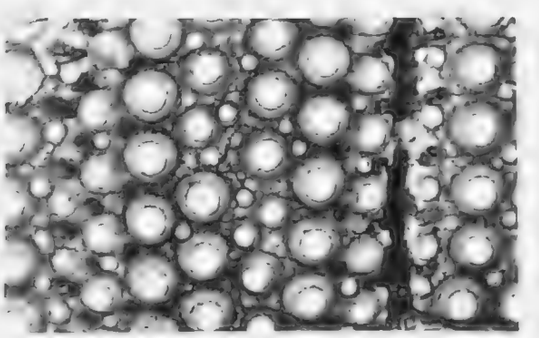
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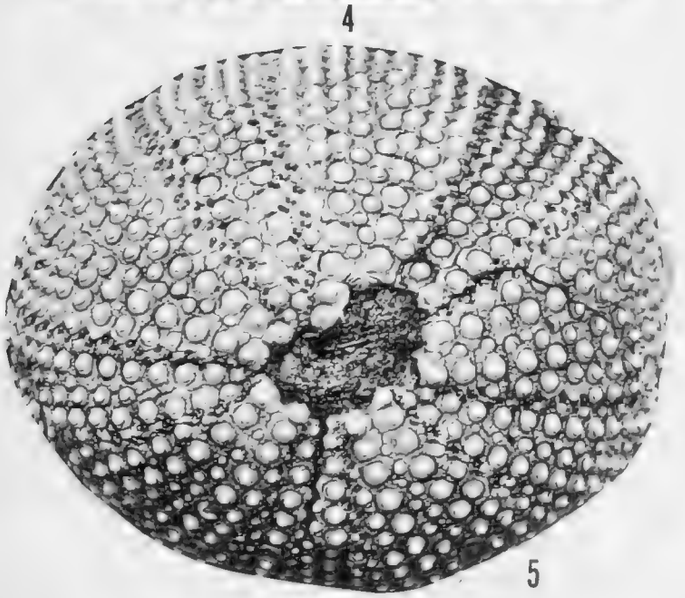
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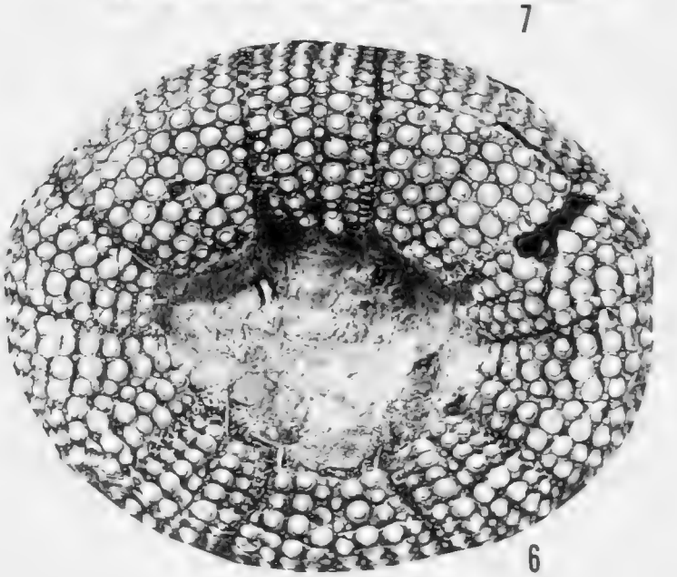
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# Teleost Fish Otoliths from Lee Creek Mine, Aurora, North Carolina (Yorktown Formation: Pliocene)

*John E. Fitch and Robert J. Lavenberg*


## ABSTRACT

Pliocene fossiliferous exposures at the Lee Creek Mine, Yorktown Formation, deposits yielded 8808 teleost otoliths. These represented at least 45 taxa distributed among 17 teleostean families including the following numbers of species by genus: Agonidae? (1), Ammodytidae (1), Bothidae (2, possibly 3), Branchiostegidae (1), Congridae (5), Cynoglossidae (1), Gadidae (5), Merlucciidae (3), Myctophidae (1), Ophidiidae (7), Pleuronectidae (1), Pomadasyidae (1), Pterothrissidae (1), Sciaenidae (7), Serranidae (4), Triglidae (2, possibly 3), Uranoscopidae (2). Generic names were assigned to 27 kinds of otoliths: *Ammodytes*, *Anisotremus*, *Astroscopus*, *Brotula*, *Centropristis*, *Ceratoscopelus*, *Citharichthys*, *Cynoscion*, *Diplectrum*, *Equetus*, *Gadus*, *Kathetostoma*, *Leiostomus*, *Lepophidium*, *Lopholatilus*, *Melanogrammus*, *Merlangiogadus*, *Merluccius*, *Microgadus*, *Micropogonias*, *Ophidion*, *Pogonias*, *Prionotus*, *Pterothrissus*, *Sciaenops*, *Symphurus*, *Urophycis*. Twenty-two of these represent the first North American Pliocene record for the genus (*Anisotremus*, *Astroscopus*, *Brotula*, *Centropristis*, *Cynoscion*, *Diplectrum*, *Equetus*, *Gadus*, *Kathetostoma*, *Leiostomus*, *Lepophidium*, *Lopholatilus*, *Melanogrammus*, *Merlangiogadus*, *Microgadus*, *Micropogonias*, *Ophidion*, *Pogonias*, *Prionotus*, *Pterothrissus*, *Symphurus*, *Urophycis*). Of these, six represent the initial fossil record anywhere (*Astroscopus*, *Diplectrum*, *Equetus*, *Kathetostoma*, *Leiostomus*, *Lopholatilus*). *Lopholatilus* represents the first fossil record for the family Branchiostegidae. Otoliths from at least two kinds of fish are from extinct genera (*Merlangiogadus* and sciaenid species A), and those of the 13 unnamed taxa may represent extinct species. Individuals of all of the listed taxa routinely inhabit waters shallower than 200 meters, except *Ceratoscopelus* and *Merluccius albidus*. Based upon the three most abundant kinds of fish otoliths (*Lepophidium*, *Merluccius*, and sciaenid species A), comprising 88 percent of the recovered otoliths, it is suggested that the Lee Creek Mine fauna may have been deposited in depths of 60 to 100 meters.


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## Introduction

In November 1971, Peter J. Harmatuk sent one of us (JEF) 67 otoliths, representing four species, from Lee Creek Mine, and volunteered to collect additional material if we were interested. Subsequently, Mr. Harmatuk sent over 8000 additional otoliths and a sample of unscreened matrix from which we gleaned another 350. The otoliths sent by Mr. Harmatuk were picked up in the field from the fossiliferous Yorktown Formation, which overlies the phosphatic sands of the Pungo River Formation being mined by Texasgulf Inc., at Aurora, North Carolina. According to Bob H. Slaughter (personal communication), the otolith-bearing overburden being worked by Mr. Harmatuk lies above the basal Yorktown, which Slaughter found to be practically void of teleost otoliths. The 245 otoliths received from Jack H. McLellan in February 1973 added numerically to those sent by Mr. Harmatuk, but there were no additional species present.

In this report on the Lee Creek Mine otoliths, no new species will be described. In most cases inadequate comparative material and our limited firsthand knowledge of the extant Atlantic marine teleost fauna dictate the necessity for a prudent approach.

Some paleontologists have operated on the principle that any fish occurring as a fossil is unquestionably a new genus and species. Others appear to believe that all fossil fish remains of Eocene age and younger are extinct species referable to extant genera. It is our opinion that neither of these philosophies is acceptable.

In the marine Pliocene and Pleistocene of California, we have recovered perhaps 200,000 otoliths, which represent 161 species; yet only 6 of these 161 (2 gobies, 2 sciaenids, an embiotocid, and a morid) cannot be referred to living species. On the other hand, a Pliocene freshwater deposit in Kettleman Hills, California, has yielded 40,000 otoliths from 10 species, and at least 8 of these are extinct. Obviously, it has been more difficult for freshwater species to survive the rigors of their environment than their marine relatives.

In the California Miocene, we have not made any critical analyses of the otolith faunas, but it would appear upon cursory examination that fewer than 50 percent of the more than 100 kinds of otoliths that have been recovered from various deposits can be assigned to extant genera. On the other hand, otoliths recovered from the Miocene and Pliocene of Maryland, Virginia, North Carolina, and Florida appear to be referable to extant genera in more than 80 percent of the cases. If, upon analysis, these percentages hold up, it is obvious that conditions that relate to survival can be much harsher in one geographic area than in another. Thus, it would appear that factors other than time have been responsible for the extinction of various taxa during the most recent 20 to 25 million years of Earth's history.

In North American Oligocene and Eocene, we have little difficulty relating otoliths to present-day families, but usually only among some of the deep-sea forms are they referable to extant genera. Cretaceous otoliths, however, have little in common with any taxonomic unit below that of order. Regardless of the time period involved, a good comparative collection is an absolute necessity for making a meaningful appraisal of fossil components at any taxonomic level.

Meyer, Slaughter, Purdy, and McLellan's faunal list (in prep.), based upon fish remains other than otoliths, does not complement our list, but this was to be expected. It is well established that teleost faunas represented by teeth and various skeletal parts are at complete odds with those represented by otoliths from the same beds or formation (cf. Casier, 1966, and Stinton, 1966). Such lack of agreement sometimes reflects poor or mistaken judgment, but even when generic names have been erroneously applied, a re-evaluation of the fauna or faunas seldom will reduce the conflict.

During 1968, Fitch collected in exposures of the fossiliferous Yorktown Formation at Rice's Pit, Hampton, Virginia, and along the south bank of the James River (Day's Point) near Smithfield. In a number of systematic accounts (below), we have included information on otoliths from these two collections.

ACKNOWLEDGMENTS.—We gratefully acknowledge the assistance of Peter J. Harmatuk, Bridgeton, North Carolina; Jack McLellan, Austin, Texas; and Warren C. Blow, National Museum of Natural History, Smithsonian Institution, Washington, D.C., for providing fossil otoliths. Jack and Mary Hopkins, Eureka, California; Richard and Diane McGinnis, Tacoma, Washington; and Clayton E. Ray, National Museum of Natural History, Washington, D.C., sent us fossiliferous dirt. William M. Rice, Hampton, Virginia, permitted Fitch to excavate at Rice's Pit. Shelton Applegate, Instituto de Geologia, Ciudad Universitaria, México, D.F.; and Bob H. Slaughter, Southern Methodist University, Dallas, Texas, gave us information regarding fossil localities. Richard A. Fitch spent one summer digging, screening, and sorting fossiliferous material.

Several individuals provided otoliths from contemporary Atlantic Ocean fishes for comparative material during the investigation, including Fred Berry, Miami, Florida; James Craddock, Woods

Hole Oceanographic Institution, Woods Hole, Massachusetts; Donald P. de Sylva, Institute of Marine Science, Miami; John Musick and Charles Wenner, Virginia Institute of Marine Science, Gloucester Point; Frank Schwartz, Institute of Marine Sciences, Morehead City, North Carolina; and Noel Tibbo, Fisheries Research Board of Canada, New Brunswick. The National Science Foundation (NSF) has previously supported research grants to Fitch that have allowed the accumulation of comparative materials (otoliths) without which fossil forms could not be identified. To all of these individuals and the NSF we extend our appreciation for this help.

Jack W. Schott, California Department of Fish and Game (CDFG), Long Beach, took the excellent otolith photographs; Caryl Maloof, Natural History Museum of Los Angeles County (LACM), applied her artistry in making the figures; Lawrence Reynolds, LACM, prepared photographs of the figures; and Lamonica Beasley and Terri Togiai, LACM, and Micaela Wolfe, CDFG, typed various revisions of the manuscript for us. To each of them we extend our thanks.

Finally, during a visit with Fitch in 1980, P.A.M. Gaemers, Geologisch en Mineralogisch Instituut der Rÿksuniversiteit, Leiden, whose specialty is gadiform otoliths, examined all of the Lee Creek Mine cod and hake sagittae, corrected some of our identifications and confirmed the others. We are especially grateful for his assistance.

## Systematic Account

### Pterothrissidae

(Pterothrissid Bonefishes)

*Pterothrissus* species (Figure 1A): Otoliths of *Pterothrissus* have been described from numerous Cenozoic deposits throughout Europe (Weiler, 1968; Stinton, 1975), but none of those found in North America has been named as yet. The single otolith from Lee Creek Mine, a left sagitta 8.0 mm long, is distinct from sagittae of the two living species, *P. belloci* and *P. gissu. Pterothrissus belloci*, the nearest living pterothrissid, inhabits waters off the west coast of Africa. Until now, we have not seen otoliths of *Pterothrissus* from the North American Pliocene, but they are present, though never abundant, in many Oligocene and Eocene deposits.

### Congridae

(Conger Eels)

Otoliths of conger eels are extremely abundant in North American Eocene deposits (Frizzell and Lamber, 1962; Frizzell and Dante, 1965:698; J.E. Fitch, unpublished data) and are plentiful in both Oligocene and Miocene, but it is very difficult to distinguish species from otoliths alone. Most of this difficulty lies in the fact that comparative material from Recent species is unavailable; without knowing the range of specific variation it is impossible to distinguish more than a minimum of the fauna. Most congrids are secretive in their habits and thus rarely are collected. Those which are collected usually are preserved intact—a standard operating procedure of eel specialists, but one which usually renders useless for taxonomic purposes the contained otoliths. Because of these factors, we do not envision a clarification of the fossil record for this family in the foreseeable future. However, papers such as that of Kotthaus (1968) will prove extremely helpful, because he illustrates otoliths of six of the eight congrid genera that he discussed from the Indian Ocean. Although somewhat etched by formalin preservation, these otoliths represent comparative material that will help to provide an understanding of fossil conger eels.

Robins et al. (1980) and Smith and Kanazawa (1977) list 11 species of congrids known to occur along the Atlantic and Gulf coastal states, and four of these also inhabit Bahaman waters (Böhlke and Chaplin, 1968:88–94). Among the 275 congrid otoliths on hand from Lee Creek Mine (Table 1), there are five discernible species.

Congrid species A (Figure 1B) is similar to "*Conger*" *sanctus* of Frizzell and Lamber (1962) (subsequently assigned to genus *Bathycongrus* by

TABLE 1.—Otoliths from the Yorktown Formation (Pliocene) of the Lee Creek Mine (dash indicates absent)

| Family and species | Number of otoliths | | Fossil record for the genus[3] | |
|---|---|---|---|---|
| | Eye[1] | Microscope[2] | First ever | First North American Pliocene |
| PTEROTHRISSIDAE | | | | |
| *Pterothrissus* species | 1 | – | | x |
| Congridae | | | | |
| Congrid species A | 99 | 1 | | |
| Congrid species B | 164 | 7 | | |
| Congrid species C | – | 2 | | |
| Congrid species D | 1 | – | | |
| Congrid species E | – | 1 | | |
| MYCTOPHIDAE | | | | |
| *Ceratoscopelus maderensis* | 13 | 31 | | |
| GADIDAE | | | | |
| *Gadus* cf. *morhua* | 1 | – | | x |
| *Melanogrammus* cf. *aeglefinus* | 1 | – | | x |
| *Merlangiogadus cognatus* | 16 | 3 | | x |
| *Microgadus* cf. *tomcod* | 8 | – | | x |
| *Urophycis tenuis* | 26 | 7 | | x |
| MERLUCCIIDAE | | | | |
| *Merluccius albidus* | 80 | 5 | | |
| *Merluccius* cf. *bilinearis* | 481 | 12 | | |
| *Merluccius* species | 373 | 11 | | |
| Unidentifiable *Merluccius* | 103 | 21 | | |
| OPHIDIIDAE | | | | |
| *Brotula barbata* | 10 | – | | x |
| *Lepophidium* cf. *cervinum* | 5610 | 130 | | x |
| *Ophidion grayi* | 24 | 4 | | x |
| Brotulid species A | 7 | – | | |
| Brotulid species B | 3 | 1 | | |
| Ophidiid species A | – | 2 | | |
| Ophidiid species B | 3 | 2 | | |
| SERRANIDAE | | | | |
| *Centropristis* cf. *striata* | 3 | – | | x |

[1] Gleaned by eye in the field.
[2] Found in washed screenings and examined under microscope.
[3] Includes only those otoliths for which a generic name is assigned.

Schwarzhans in 1976:473), but it has a more rounded posterior end and other subtle differences. Its exact generic placement cannot be determined without seeing comparative material from the congrids listed by Robins et al. (1980) and Smith and Kanazawa (1977). The 100 Lee Creek Mine otoliths that we have assigned to this species range in length from 2.8 to 10.2 mm; the figured specimen is 8.5 mm long.

Congrid species B (Figure 1c) has more than a slight resemblance to the fossil genus *Parbatmya* Frizzell, Lamber, and Dante, but we suspect that the Lee Creek Mine otoliths are referable to an extant genus. Therefore, we will leave their ge-

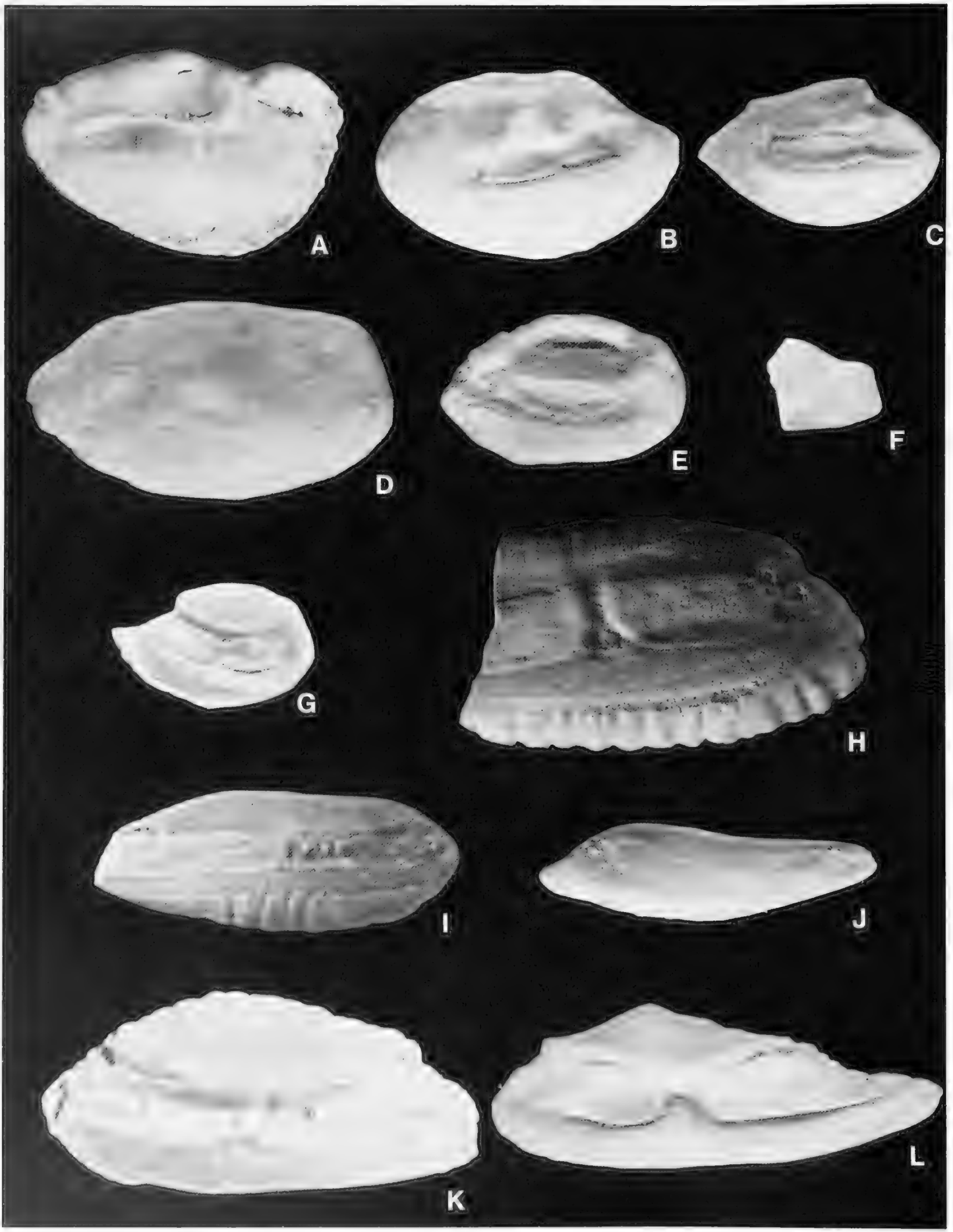
TABLE 1.—Continued.

| Family and species | Number of otoliths | | Fossil record for the genus[3] | |
|---|---|---|---|---|
| | Eye[1] | Micro-scope[2] | First ever | First North American Pliocene |
| *Diplectrum* cf. *formosum* | 16 | – | x | x |
| Serranid species A | 2 | – | | |
| Serranid species B | 1 | – | | |
| BRANCHIOSTEGIDAE | | | | |
| *Lopholatilus chamaeleonticeps* | 14 | 1 | x | x |
| POMADASYIDAE | | | | |
| *Anisotremus* species | 16 | – | | x |
| SCIAENIDAE | | | | |
| *Cynoscion* cf. *nebulosus* | 308 | 11 | | x |
| *Equetus* cf. *umbrosus* | 7 | – | x | x |
| *Leiostomus* species | 31 | 5 | x | x |
| *Micropogonias* species | 32 | 2 | | x |
| *Pogonias* cf. *cromis* | 1 | – | | x |
| *Sciaenops* cf. *ocellata* | 3 | – | | |
| Sciaenid species A | 929 | 1 | | |
| URANOSCOPIDAE | | | | |
| *Astroscopus* species | 23 | – | x | x |
| *Kathetostoma* species | 12 | – | x | x |
| AMMODYTIDAE | | | | |
| *Ammodytes hexapterus* | 1 | 6 | | |
| TRIGLIDAE | | | | |
| *Prionotus* spp. | 17 | 12 | | x |
| BOTHIDAE | | | | |
| *Citharichthys* spp. | 15 | 62 | | |
| PLEURONECTIDAE | | | | |
| Pleuronectid | – | 1 | | |
| CYNOGLOSSIDAE | | | | |
| *Symphurus* species | 1 | 10 | | x |
| AGONIDAE? | | | | |
| Unknown | – | 1 | | |

neric assignment to the future. The 171 otoliths belonging to this species range in length from 2.0 to 7.3 mm; the figured specimen is 6.7 mm long.

Congrid species C (Figure 1D) has a relatively flat inner face and a deeply convex outer face. It is distinct from any of the species described by Frizzell and Lamber (1962) and cannot be assigned generically at this time. These two otoliths (Table 1) are 2.5 and 2.7 mm long, and the larger is figured.

Congrid species D (Figure 1E) is represented by a single right sagitta, 4.2 mm long, which, although somewhat abraded, is readily recognizable as belonging to this family.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Congrid species E (Figure 1F) is represented by the posterior half only of a right sagitta. This fragment is 2.7 mm long and is unquestionably from *Conger*, sensu stricto, which has a unique otolith, not only among congrids but among other eels regardless of family. One otolith from Rice's Pit, Virginia, is also from the genus *Conger*, but we have not attempted to relate the numerous other congrid otoliths from Rice's Pit and Day's Point to the other four species (A, B, C, and D, above) from Lee Creek Mine.

### Myctophidae

(Lanternfishes)

*Ceratoscopelus maderensis* (Lowe), horned lanternfish (Figure 1G): The 44 lanternfish otoliths from Lee Creek Mine are all from this species, which today inhabits waters of the North Atlantic between north latitudes 22° and 50° (Bolin, 1959:38). Although Fitch (1969a:5) reported *Ceratoscopelus* otoliths from the Pliocene and Pleistocene of California, they were not from this species. The Lee Creek Mine otoliths are the first fossil record for the species. The 44 otoliths (Table 1) ranged in length from 2.1 to 3.8 mm with most exceeding 3.0 mm; the figured otolith is 3.4 mm long. The sagittae from a 72 mm standard length *C. maderensis* were 3.7 mm long.

### Gadidae

(Cods)

*Gadus* cf. *morhua* Linnaeus, Atlantic cod (Figure 1H): A single, broken left sagitta was from a *Gadus*, probably *G. morhua* that inhabits the North Atlantic today, but in its broken condition exact specific assignment cannot be made with certainty. The southern limit of distribution for *G. morhua* in North American waters generally is noted as "off Cape Hatteras, N.C." (Leim and Scott, 1966:196). The Lee Creek Mine otolith is 11.8 mm long; it would have exceeded 16 mm if unbroken. There is no previous fossil record for the genus from North America, although sagittae of *G. macrocephalus* have been recovered from Ice Age deposits in the Aleutians (J. Fitch, unpublished data).

*Melanogrammus* cf. *aeglefinus* (Linnaeus), haddock (not figured): A single, broken left sagitta was from *Melanogrammus*, probably *M. aeglefinus*, which inhabits North American waters as far south as Cape Hatteras, North Carolina during winter months (Leim and Scott, 1966:203). In its broken condition, however, assignment to this species cannot be made with any degree of certainty. Gaemers and Schwarzhans (1973:215, pl. 1, figs. 22a, b, 23; pl. 4, figs. 5a, b) described and figured sagittae from an extinct species of *Melanogrammus* from the Pliocene of Belgium, and Gaemers (1976) restricted *M. aeglefinus* to the post-Pliocene. The broken fragment from the Lee Creek Mine is the anteriormost 11.9 mm of an otolith that would have exceeded 17 mm if entire. There is no previous fossil record for the genus from North America, although *Melanogrammus* otoliths were present also at Rice's Pit and Day's Point.

*Merlangiogadus cognatus* (Koken), extinct gadid (not figured): Nineteen otoliths (Table 1), mostly broken and badly eroded, were from this extinct gadid. This genus was established by Gaemers (1973) for Koken's *Otolithus cognatus*. The otoliths of *Merlangiogadus* are most similar in outline to those of *Merlangius* and *Micromesistius*, but they differ from these two genera in several salient features, according to Gaemers (1973). In the degree of convexity along the long axis, sagittae of *Merlangiogadus* are most similar to those of *Melanogrammus*, but again, there are differentiating characters. Gaemers (1973) assigns two species to the genus: *M. decorus* from European Oligocene

Figure 1.—Fish otoliths found in deposits from Lee Creek Mine, Yorktown Formation (length, in mm, is given for each otolith; notation is made regarding its position in the skull, left or right; otolith condition is noted if imperfect; all are sagittae, and all views are inner faces): A, *Pterothrissus* species, 8.0, l, worn; B, Congridae species A, 8.5, l; C, Congridae species B, 6.7, l; D, Congridae species C, 2.7, r; E, Congridae species D, 4.2, r; F, Congridae species E, 1.8, r, anterior half missing; G, *Ceratoscopelus maderensis*, 3.4, r; H, *Gadus* cf. *morhua*, 11.8, l, broken and worn; I, *Microgadus* cf. *tomcod*, 10.2, l, broken and worn; J, *Urophycis tenuis*, 9.4, l; K, *Merluccius albidus*, 12.3, r, broken and worn; L, *Merluccius bilinearis*, 17.6, r.

and *M. cognatus* from lowermost middle Miocene and upper Miocene. The Lee Creek Mine otoliths represent the first report of *Merlangiogadus* from North America, although Eastman (1904, pl. 32, figs. 17, 18) illustrated them from Calvert Cliffs, Maryland. Dante apparently considered the *Merlangiogadus* otolith figured by Eastman as being from sciaenids as noted in the following quotation from Dante (1953:878): "Eastman (1904, pl. 32, figs. 17–19), in his report on the Maryland Miocene, figured two otoliths but did not describe them. These otoliths appear to belong to a sciaenid." Actually, Eastman's figures 17 and 18 are of *Merlangiogadus*, and only his figure 19 is of a sciaenid. Fitch (ms) found that otoliths of *M. cognatus* are abundant in Calvert Cliffs, Maryland, deposits (St. Mary's and Calvert formations). If entire, the 19 Lee Creek Mine otoliths would have ranged from about 6.5 to 14 mm long.

*Microgadus* cf. *tomcod* (Walbaum), Atlantic tomcod (Figure 1I): Eight of the Lee Creek Mine otoliths (Table 1) could be assigned to *Microgadus*, but because all were worn and broken, their specific assignment cannot be made with certainty as they may represent an extinct species. Although gadid otoliths from the Eocene of England have been assigned to this genus (Stinton, 1977:91), a careful analysis probably will show that they are not congeneric. Otoliths of *M. proximus*, an extant species, have been reported from the Pleistocene of California (Fitch, 1967:10, 1970:27), but the Lee Creek Mine otoliths represent the first report of *Microgadus* from the Pliocene of North America. If entire, these 8 otoliths would have ranged in length from about 10 to more than 17 mm; the figured otolith is 10.2 mm long.

*Urophycis tenuis* (Mitchill), white hake (Figure 1J): The 33 *Urophycis* sagittae from Lee Creek Mine match only those of *U. tenuis* from among the six species listed by Robins et al. (1980) as inhabiting waters of the western North Atlantic. *Urophycis tenuis* (Koken) has been reported as a fossil from European deposits (Weiler, 1968:35; Dieni, 1969:266), but based upon material in the Fitch fossil collection, these may be from juvenile *Brotula*. If, however, they are assigned correctly at the generic level, they will need a new specific name, because *tenuis* of Mitchill predates Koken's *tenuis* by more than 75 years. The genus previously has not been reported as a fossil from North America. *Urophycis* otoliths (more than one species) were also found at Day's Point and Rice's Pit. The 33 otoliths from Lee Creek Mine were mostly broken and worn, but if entire they would have ranged from about 9.4 to 17 mm long; the figured specimen is 9.4 mm long.

## Merlucciidae

(Hakes)

*Merluccius albidus* (Mitchill), offshore hake (Figure 1K): Of the 1086 *Merluccius* otoliths from Lee Creek Mine, 85 (Table 1) were from *M. albidus*, but none of these was in perfect condition. According to Ginsburg (1954:193) and Leim and Scott (1966:205), *M. albidus* ranges from off Georges Bank to Cape Canaveral, at least, and the adults generally are found in depths exceeding 200 m. *Merluccius* otoliths have been reported from Cenozoic deposits throughout much of the world, but only *M. productus* from the Pliocene and Pleistocene of California (Fitch, 1969b:72, 78, 1970:27) has been reported from North America. In one Pliocene deposit of California, *M. productus* otoliths comprised more than 13 percent of the total otoliths recovered; in the Lee Creek Mine material they comprised about the same percentage, but these figures are not comparable because otolith recovery methods differed. *Merluccius albidus* otoliths also were present at Rice's Pit and Day's Point in Virginia. If entire, the 85 *M. albidus* otoliths from Lee Creek Mine would have ranged in length from about 9 to more than 15 mm; the figured specimen, a broken right sagitta, is 12.3 mm long.

*Merluccius* cf. *bilinearis* (Mitchill), silver hake (Figure 1L): The most abundant *Merluccius* otoliths in the Lee Creek Mine material matched those of *M. bilinearis* sufficiently well that they unquestionably are from an extinct ancestor, if not from the extant *M. bilinearis*. In all, 493 (Table 1) of the 1086 *Merluccius* otoliths could be assigned

here; most were broken or badly eroded, or both, but if entire, they would have ranged in length from shorter than 10 to longer than 24 mm. Otoliths of this species were present at Rice's Pit and Day's Point, also.

*Merluccius* species, extinct hake (not figured): The Lee Creek Mine material contained 384 otoliths (Table 1) from an extinct species of *Merluccius*. Otoliths of these differ from sagittae of the two nominal species of *Merluccius* that inhabit the western North Atlantic in numerous features, most notable being the thickness of the otolith, the width and depth of the sulcus, the marginal ornamentation, and the predorsal angularity. In contrast to the other two species, a number of the otoliths from this extinct form were entire. Total lengths of the 384 otoliths would have ranged from about 10 to 28 mm in length.

*Merluccius* spp., unidentifiable: Among the 1086 hake otoliths from Lee Creek Mine, 124 were too badly fragmented or eroded to be assigned to any of the above three species.

## Ophidiidae

(Cusk-eels and Brotulas)

Cohen and Nielsen (1978) in defining the fish order Ophidiiformes included keys to families and genera, and gave estimates of numbers of species by genus. As they defined the order, it comprises 4 families, 82 genera, and some 300 to 400 species. Based upon their publication, Nolf (1980) figured with line drawings sagittae from 70 of the 82 recognized genera, and presented a "revision" of fossil ophidiids that have been described from otoliths. Unfortunately, his reassignment of several perfectly good fossil genera to taxonomically unacceptable categories (e.g., *Preophidium stintoni* Dante and Frizzell to "*Neobythitinarum*" *stintoni*, *Signata nicoli* Dante and Frizzell to "*Ophidiidarum*" *nicoli*) forces one to question the validity of many of his other generic assignments. Similarly, the philosophy of Nolf, and several other contemporary European paleontologists, that all fossil otoliths of Eocene or younger age must be assigned or equated to extant genera, often indiscriminately, casts serious doubt in the minds of many ichthyologists as to the usefulness of otoliths as taxonomic tools.

The seven kinds of ophidiid otoliths from Lee Creek Mine would appear to belong to family Ophidiidae as defined by Cohen and Nielsen (1978), but generic assignments cannot be made for some because we lack what we consider to be critical comparative material from the western North Atlantic.

*Brotula barbata* (Bloch and Schneider), bearded brotula (Figure 2A): Although otoliths of *Brotula* have been reported from the London Clay (Eocene) by Stinton (1966:430) and from the Miocene of Trinidad by Nolf (1976:723), they have not been reported from North America until now. Because of their resemblance to otoliths of some gadids (e.g., *Urophycis*), especially when small, we suspect that some of the European fossil gadid records that are based upon otoliths alone are actually *Brotula*. Fitch has sagittae from five species of *Brotula* in his comparative collection, but we can find no character or combination of characters for distinguishing any one of the five from the other four. Because of this, and since *B. barbata* is the only species presently known to inhabit waters off the Atlantic coastal states; it seems reasonable to assign that specific name. All 10 of the *Brotula* otoliths from Lee Creek Mine are broken, but if entire, they would have measured approximately 15 to 30 mm long; the figured specimen is 15.9 mm long to where broken.

*Lepophidium* cf. *cervinum* (Goode and Bean), fawn cusk-eel (Figure 2B): This was by far the most abundant otolith found in Lee Creek Mine (Table 1), comprising 71 percent of the collected sagittae. Unfortunately, we have comparative material from only 2 of the 13 western North Atlantic species of cusk-eels listed by Robins et al. (1980); but because of their unique shape, we hesitantly refer them to *L. cervinum* with which they agree rather closely. Some of the Lee Creek Mine "*L. cervinum*" otoliths are much more elongate and less high, however; and we suspect that these may represent a second species with a projecting (pointed) anterodorsal corner. A fair number of these *Lepophidium* otoliths from Lee Creek

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Mine are freakishly developed and would have appeared glassy and crystalline if from living fishes. Frizzell and Exline (1958), Weiler (1959), Jónsson (1966), and Mugiya (1972) have noticed this phenomenon among fishes that they examined, but only Mugiya (1972) investigated the mineralogy of these aberrant otoliths. We have had a number of these freakishly developed glassy otoliths analyzed and all have turned out to be calcite and vaterite as compared to aragonite for their normally developed counterparts. Palmork, Taylor, and Coates (1963) reported upon the chemical composition of two types of these freakishly formed otoliths, which they found in the cod *Gadus morhua.* Based upon X-ray powder analyses, their Type 1 otoliths contained a mixture of vaterite and calcite, whereas accretions from their Type 2 contained calcite only. A reasonable assumption for living fishes is that something in the fish's environment is inhibiting its ability to metabolize calcium; the same could have been true for the fossils.

Among otoliths of ophidiids, the sulcus (groove on inner face) may be divided vertically or horizontally with several variations of proportion, width, or configuration. This division of the sulcus is unquestionably of taxonomic importance, but to what extent has not been investigated as yet. The 5740 *Lepophidium* otoliths from Lee Creek Mine ranged from 2.2 to slightly longer than 9.0 mm; the figured specimen is 7.6 mm long. Previously, otoliths of *Lepophidium* have been reported from the Pleistocene of California (Fitch, 1970:25) from the Pliocene and Miocene of Trinidad (Nolf, 1976:723), and from the Eocene of England (Stinton, 1965:407) and Belgium (Nolf, 1974). *Lepophidium* otoliths among those from Day's Point and Rice's Pit apparently are referable to *L. cervinum* also.

*Ophidion grayi* (Fowler), blotched cusk-eel (Figure 2C): Otoliths of this species have a concave outer face, and the sulcus is divided longitudinally. These two features in combination with their generally oval outline are sufficient to distinguish *O. grayi* sagittae from those of other cusk-eels that we have seen. Robins et al. (1980) list six species of *Ophidion* as inhabiting waters of the western North Atlantic, and Böhlke and Chaplin (1968:168) report a sixth at the Bahamas. Among these, we have comparative material only from *O. grayi*, *O. holbrooki*, and *O. welshi.* Otoliths of *O. grayi* are also present at Day's Point and Rice's Pit. The 28 sagittae from Lee Creek Mine range in length from 2.8 to 8.4 mm; the figured specimen is 7.6 mm long.

Otoliths have been assigned to this genus from fossil deposits in Europe and the Barbados, but not from North America proper. Those described from Barbados (Casier, 1958) do not appear to be from an ophidiid.

Brotulid species A (Figure 2D): Seven otoliths among the Lee Creek Mine material have a sulcus that is divided vertically near the posterior end, and a concave posterodorsal corner that gives it a slightly twisted appearance at that point. The sulcal surface (inner face) is evenly rounded dorsoventrally and from front to rear. These seven otoliths range in length from 5.2 to 6.4 mm; the figured specimen is 5.4 mm long.

Brotulid species B (Figure 2E): Four otoliths from Lee Creek Mine, which also have a sulcus that is divided vertically near its posterior end, lack the concave posterodorsal corner of the "brotulid species A" otoliths and have an almost flat inner face. These four otoliths range in length from 4.3 to 5.5 mm; the largest individual is figured.

Ophidiid species A (Figure 2F): Two small ophidiid otoliths from the Lee Creek Mine bulge in outline both dorsally and ventrally, and at that point are almost as tall as they are long. The sulcus is divided longitudinally. These otoliths,

FIGURE 2.—Fish otoliths found in deposits from Lee Creek Mine, Yorktown Formation (length, in mm, is given for each otolith; notation is made regarding its position in the skull, left or right; otolith condition is noted if imperfect; all are sagittae, and all views are inner faces): A, *Brotula barbata*, 15.9, r, broken; B, *Lepophidium* cf. *cervinum*, 7.6, r; C, *Ophidion grayi*, 7.6, l; D, Brotulidae species A, 5.4, r; E, Brotulidae species B, 5.5, r; F, Ophidiidae species A, 2.0, l; G, Ophidiidae species B, 2.8, l; H, *Centropristis* cf. *striata*, 8.2, r, worn; I, *Diplectrum* cf. *formosum*, 8.1, r, broken and worn; J, Serranidae species A, 10.5, l, broken, tip of rostrum missing; K, Serranidae species B, 11.2, r, broken, anterior portion missing.

2.0 and 2.1 mm long are similar if not identical to some ophidiid otoliths in the Pliocene Bowden Formation of Jamaica (J.E. Fitch, unpublished data).

Ophidiid species B (Figure 2G): Five of the Lee Creek Mine ophidiid otoliths with a longitudinally divided sulcus are teardrop-shaped and quite thick. The outer face of these otoliths, which range in length from 2.2 to 4.4 mm, is convex. These otoliths also occur at Day's Point and Rice's Pit. A lack of comparative material prevents our speculating as to generic or specific affinities of these and the preceding three kinds.

### Serranidae

(Sea Basses)

*Centropristis* cf. *striata* (Linnaeus), black sea bass (Figure 2H): Three otoliths are unquestionably serranids and among the serranid genera found in the western North Atlantic they agree in all salient features with *Centropristis*. Of the four species of *Centropristis* listed by Robins et al. (1980), comparative material was unavailable from *C. fuscula*; but among the other three, *C. striata* had the only otolith with a notch in the ventral profile beneath the terminus of the cauda or posterior portion of the sulcus. The fossil otoliths, however, are much thicker at comparable sizes than sagittae of living *C. striata*. Two of the three Lee Creek Mine otoliths have pieces missing, but if entire, they would have been about 7.1 to 9.0 mm long; the figured specimen is 8.2 mm long. Otoliths from several European deposits have been assigned to *Centropristis*, but the Lee Creek Mine specimens are the first fossil record from North America. Similar appearing serranid otoliths occur at Day's Point and Rice's Pit, but we have not attempted to determine generic affinities for these as yet.

*Diplectrum* cf. *formosum* (Linnaeus), sand perch (Figure 2I): These 16 otoliths (Table 1) superficially are quite similar to otoliths of *Centropristis*, but several subtle differences of configuration, proportions, and angles are consistent with the comparative material at hand. The 16 Lee Creek Mine otoliths are all either worn, broken, or both, but if entire, they would have ranged from about 6.5 to longer than 10 mm; the figured specimen is 8.1 mm long as is. Of the three species of *Diplectrum* inhabiting waters of the western Atlantic (Bortone, 1977:11, 22, 26), comparative material was unavailable from *D. bivittatum*, but it is a more southerly occurring species than *D. formosum*, to which we hesitantly assign the fossils. The Lee Creek Mine otoliths are much thicker at comparable sizes than those from living *D. formosum*, but otherwise they agree quite well. There is no previous fossil record for the genus.

Serranid species A (Figure 2J): Two otoliths, unquestionably from serranids, have a cauda that turns down at a 90° angle. Both have the rostrum tip missing; but if entire, they would have been about 10.5 and 13 mm long; the smaller specimen is illustrated. It is not possible to make a generic assignment from the material at hand.

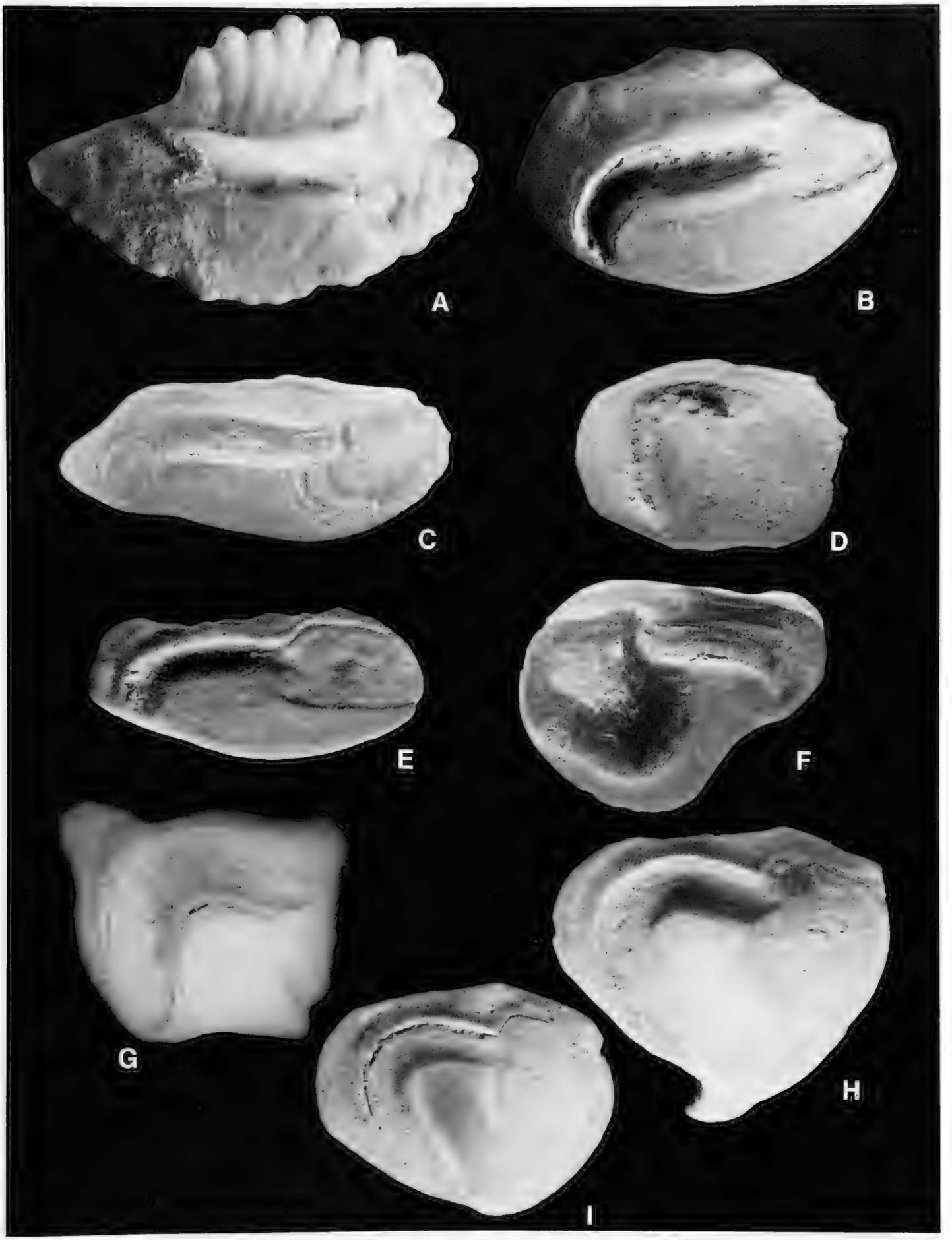
Serranid species B (Figure 2K): The straight ventral margin, frilly edges, rounded posterior end, large size, and extraneous projecting bits of aragonitic material, which are observable on this broken otolith suggest an affinity with either *Polyprion* or *Lobotes*. Without seeing the anterior half of this otolith, however, it is impossible to make a more definitive identification. The broken posterior portion is 11.2 mm long.

### Branchiostegidae

(Tilefishes)

*Lopholatilus chamaeleonticeps* Goode and Bean, tile fish (Figure 3A): At first glance, tilefish otoliths might be mistaken for those from some of

FIGURE 3.—Fish otoliths found in deposits from Lee Creek Mine, Yorktown Formation (length, in mm, is given for each otolith; notation is made regarding its position in the skull, left or right; otolith condition is noted if imperfect; all sagittae, and all views are inner faces): A, *Lopholatilus chamaeleonticeps*, 12.5, r, worn; B, *Anisotremus* species, 10.8, l, worn; C, *Cynoscion* cf. *nebulosus*, 11.0, l; D, *Equetus* cf. *umbrosus*, 6.7, l, worn; E, *Leiostomus* species, 8.3, l; F, *Micropogonias* species, 8.8, r; G, *Sciaenops* cf. *ocellata*, 17.0, l, broken; H, Sciaenidae species A, 8.4, l, with spur; I, Sciaenidae species A, 7.5, l, without spur.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the scorpaenids (Scorpaenidae), but the abrupt, straight-line termination of the crista superior (a ridge parallel to and rimming the sulcus dorsally) of *Lopholatilus* otoliths is unique. This characteristic crista superior, the massive otolith size, and general otolith outline preclude assigning these sagittae to any other genus. There is no previous fossil record for this family, and to our knowledge, tilefish otoliths have not been found in any other deposit. Wigley and Stinton (1973:28, 33, fig. 18L, 21) reported finding tilefish otoliths in bottom sediments taken from 113 m off Massachusetts, however. The 15 *Lopholatilus* otoliths from Lee Creek Mine are mostly broken, but if entire, they would have ranged in length from about 5 to 18 mm; the figured specimen is 12.5 mm long.

## Pomadasyidae

(Grunts)

*Anisotremus* species (Figure 3B): We have no hesitation in assigning these 16 otoliths to the genus *Anisotremus*, but a lack of comparative material from western Atlantic species precludes making specific identifications. *Anisotremus davidsonii* has been reported from the Pleistocene of California (Fitch, 1970:17), but this is the first report of the genus from the Pliocene. These 16 otoliths are mostly worn or broken, but if entire, they would have ranged from about 7 to longer than 11 mm; the figured specimen is 10.8 mm long.

## Sciaenidae

(Drums)

*Cynoscion* cf. *nebulosus* (Cuvier), spotted seatrout (Figure 3C): Of the four species of *Cynoscion* that presently inhabit waters of the Atlantic and Gulf coastal states (Robins et al., 1980), the 319 otoliths from Lee Creek Mine (Table 1) agree quite well with sagittae from *C. nebulosus*. Other species may be present among these fossils, but due to their generally poor condition, we did not make the necessary comparisons. The posterior ends of the other three species are much rounder and broader than those of *C. nebulosus*. If entire, these otoliths would have ranged in length from about 5 to 18 mm at least; the figured specimen is 11.0 mm long. *Cynoscion* otoliths are present at Day's Point and Rice's Pit, as well as in the Tertiary of Florida, but we have not tried to distinguish species for these as yet. Previously, two species of *Cynoscion* have been reported from the Pleistocene of California (Fitch, 1970:21) and the genus has been reported from the Miocene of Trinidad (Nolf, 1976:729), but this is the first record of the genus from North American Pliocene.

*Equetus* cf. *umbrosus* Jordan and Eigenmann, cubbyu (Figure 3D): The seven *Equetus* sagittae from Lee Creek Mine match those of *E. umbrosus* quite well, but we have not seen otoliths of *E. punctatus* from among the four species noted by Robins et al. (1980) as inhabiting waters of the western North Atlantic. There is no previous fossil record for the genus, and we did not find *Equetus* otoliths in the Virginia exposures. The Lee Creek Mine otoliths range in length from just under 6.0 mm to slightly over 9.0 mm; the illustrated specimen is 6.7 mm long.

*Leiostomus* species (Figure 3E): These 36 otoliths, while unquestionably from a species of *Leiostomus*, differ from *L. xanthurus*, the only extant species, in so many features that they probably represent an extinct form. These 36 otoliths range in length from 6.0 to 9.4 mm; the illustrated specimen is 8.3 mm long. There is no previous fossil record for the genus.

*Micropogonias* species (Figure 3F): Roux (1973) and Chao (1978) have presented convincing arguments for substituting *Micropogonias* for the fish genus name *Micropogon* that is preoccupied by the bird genus *Micropogon*. Otoliths of the two species known to inhabit western Atlantic waters also are discussed and illustrated (with line drawings) by Chao (1978:19, 32, 33; figs. 26,39). The 34 *Micropogonias* otoliths from Lee Creek Mine differ consistently in several salient features from those of *M. undulatus*, the only species now living in western Atlantic coastal waters north of Campeche Bay, Mexico. They differ even more widely from oto-

liths of *M. furnieri*, a more southerly ranging species in the western Atlantic. Previously, fossil otoliths found in the Californian Pleistocene (Fitch, 1970:27) and the Neogene of Sumatra (Frost, 1925:16) have been assigned to *Micropogonias*. Those from Sumatra, however, are very likely from one of the Indian Ocean genera, otoliths of which were illustrated by Mohan (1969, fig. 2) and Trewavas (1977). Most of the Lee Creek Mine *Micropogonias* otoliths are broken, but if entire, they would have ranged from about 5.5 to longer than 13.5 mm; the illustrated specimen is 8.8 mm long.

*Pogonias* cf. *cromis* (Linnaeus), black drum (not illustrated): One small (6.1 mm long), badly chipped otolith from Lee Creek Mine is unquestionably from *Pogonias*. The inner face is concave and it has a sharply pointed, slightly projecting posterodorsal corner that is unique to *Pogonias*. In these features and other characters it agrees well with otoliths of *P. cromis*. There is no previous North American record for this genus.

*Sciaenops* cf. *ocellata* (Linnaeus), red drum (Figure 3G): One nearly complete but badly worn otolith, and two half otoliths from Lee Creek Mine were from *Sciaenops*. The projecting spur on the posterodorsal corner, the shape of the cauda and angle of curvature, and the squared-off posterior margin are unique to *Sciaenops* and agree quite well with otoliths of *S. ocellata*. Previously, *S. eastmani* was described by Dante (1953) from Calvert Cliffs (Miocene) of Maryland; Fitch considers it to be a synonym of *S. ocellata* (Fitch, ms). The figured specimen from Lee Creek Mine is 17.0 mm to the break, and if entire, would have been longer than 30 mm; the smallest of the three was 11.0 mm long.

Sciaenid species A (Figure 3H,I): These disc-shaped otoliths with a sweeping loop in the cauda apparently represent an extinct genus. Perhaps 20 percent of the 930 otoliths have a projecting spur on the anteroventral corner (Figure 3H). Although none was found in the two Yorktown Formation outcrops in Virginia, there are 19 small otoliths of this species in some Miocene material from Calvert Cliffs, Maryland (Fitch, ms). The 930 Lee Creek Mine otoliths range in length from 5.2 to 11.1 mm; the figured specimens are 7.5 (without spur) and 8.4 mm long.

## Uranoscopidae

(Stargazers)

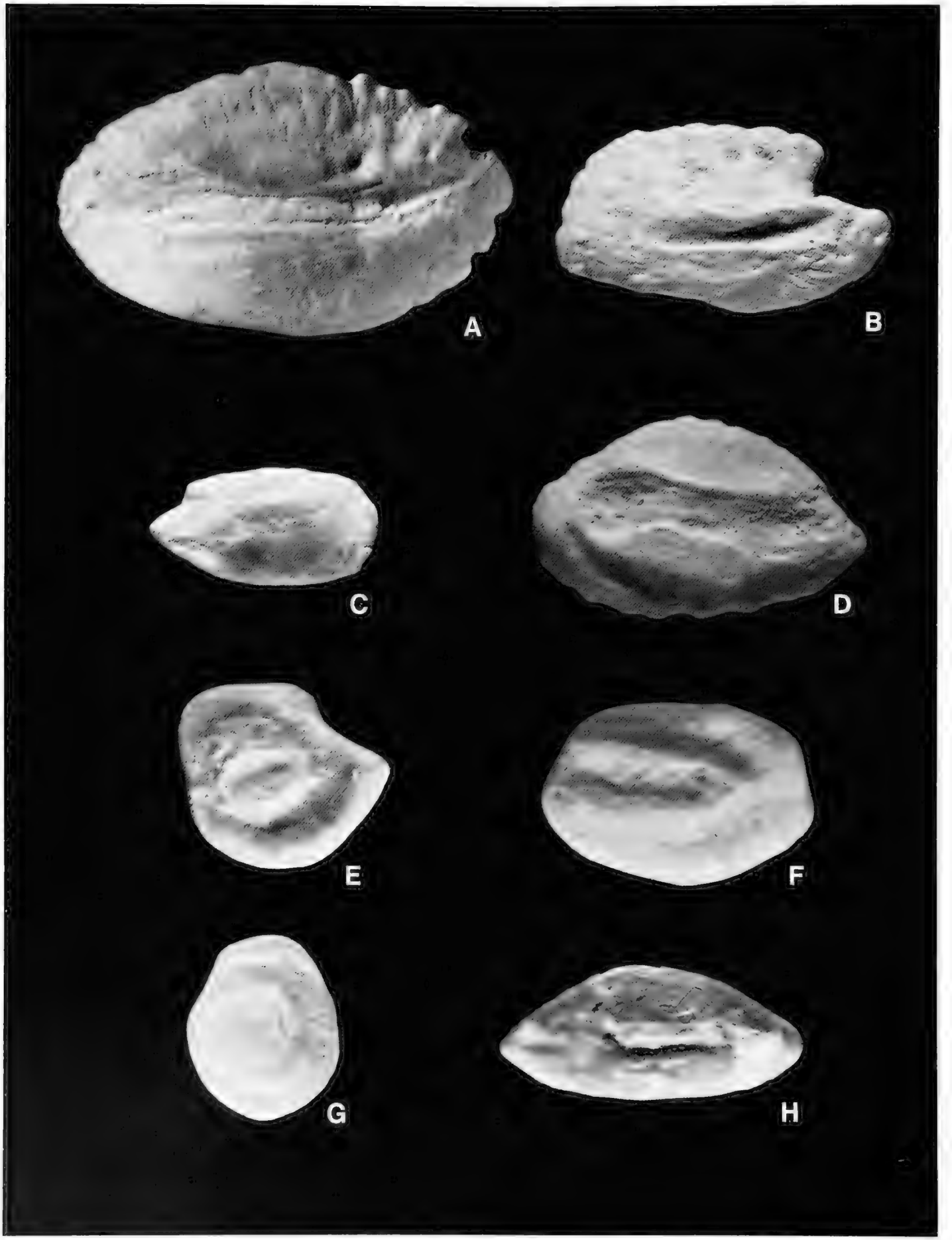
*Astroscopus* species (Figure 4A): These 23 otoliths from Lee Creek Mine agree very well with those of *Astroscopus* otoliths from the eastern Pacific, but we lack comparative material from the two species listed by Robins et al. (1980) from western North Atlantic; thus we cannot speculate as to their specific assignment. Otoliths of this species were present also at Day's Point and Rice's Pit. The 23 Lee Creek Mine *Astroscopus* otoliths range in length from slightly less than 6.0 mm to just over 15.0 mm; the figured specimen is 14.0 mm long. There is no previous fossil record for *Astroscopus*.

*Kathetostoma* species (Figure 4B): Only one species of *Kathetostoma* inhabits Atlantic waters within the area of concern (Robins et al., 1980), but since we lack comparative material of that species, we are unable to speculate as to the specific affinities of the fossils. These 12 Lee Creek Mine otoliths agree quite well with sagittae from *Kathetostoma* in the eastern Pacific, however; so we have no doubts regarding their generic assignment. *Kathetostoma* otoliths were not present in the Virginia deposits. The Lee Creek Mine *Kathetostoma* otoliths range in length from 5.0 to 9.7 mm; the figured specimen is 8.3 mm long. There is no previous fossil record for the genus.

## Ammodytidae

(Sand Lances)

*Ammodytes hexapterus* Pallas, common sand lance (Figure 4C): Although Robins et al. (1980) list three species of *Ammodytes* as occurring in the western North Atlantic within the area of concern, Richards, Perlmutter, and McAneny (1963) and Scott (1972) indicate that there are only two: *A. hexapterus* and *A. dubius*. According to Scott (1972:1675), these two species can be distinguished by their otoliths alone, but we believe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that it is desirable to compare the fossils carefully with sagittae from the living species. *Ammodytes* otoliths were the dominant sagittae (numerically) at Day's Point and were extremely abundant at Rice's Pit. Previously, *A. hexapterus* otoliths have been reported from Pliocene and Pleistocene deposits in California (Fitch, 1968:24, 1970:16), but this is the first fossil record from eastern North America. Numerous species have been reported from European fossil deposits (Weiler, 1968). The seven Lee Creek Mine *Ammodytes* otoliths ranged in length from 1.5 to 2.5 mm; the figured specimen is 2.4 mm long.

### Triglidae

(Searobins)

*Prionotus* spp. (Figure 4D): Robins et al. (1980) list 12 species of *Prionotus* as inhabiting waters off the Atlantic and Gulf coastal states. By ratios of otolith thickness into length or height, and length into height, and by differences in marginal ornamentation, and overall shape and angles, we suspect that a number of these species could be distinguished by their otoliths alone, but we have not carried out the necessary studies to prove or disprove this hypothesis. The Lee Creek Mine otoliths are unquestionably from several species of triglids. Triglid otoliths, presumably mostly *Prionotus*, were also present at Day's Point and Rice's Pit. Based upon otoliths, two species of *Prionotus* have been reported from Pleistocene deposits in California (Fitch, 1970:32), but the genus has not been noted from North American Pliocene until now. The 29 Lee Creek Mine triglid otoliths ranged in length from 2.0 to 5.8 mm; the figured specimen is 5.2 mm long.

FIGURE 4.—Fish otoliths found in deposits from Lee Creek Mine, Yorktown Formation (length, in mm, is given for each otolith; notation is made regarding its position in the skull, left or right; otolith condition is noted if imperfect; all are sagittae, and all views are inner faces): A, *Astroscopus* species, 14.0, l; B, *Kathetostoma* species, 8.3, l; C, *Ammodytes hexapterus*, 2.4, r; D, *Prionotus* species, 5.2, l; E, *Citharichthys* species, 3.5, l; F, Pleuronectidae, 1.8, r, worn; G, *Symphurus* species, 2.6, r; H, Agonidae?, 3.6, r, worn.

### Bothidae

(Lefteye Flounders)

*Citharichthys* spp. (Figure 4E): At least two species are represented among the *Citharichthys* otoliths from Lee Creek Mine, but since, for comparative purposes, we have only three of the seven Atlantic species listed by Gutherz (1967), we are not in a position to speculate as to the specific affinities of the fossils. Three species of *Citharichthys* have been reported from Pliocene and Pleistocene deposits in California (Fitch, 1970:19; Fitch and Reimer, 1967:82, 83), and the genus has been reported from the Miocene and Pliocene of Trinidad (Nolf, 1976:737); but this is the first record from the Pliocene of eastern North America. The 77 *Citharichthys* otoliths from Lee Creek Mine range in length from 1.4 to 4.1 mm; the figured specimen is 3.5 mm long. *Citharichthys* otoliths, more than one species, were also present at Day's Point and Rice's Pit.

### Pleuronectidae

(Righteye Flounders)

Pleuronectid (Figure 4F): One Lee Creek Mine otolith, although small and worn, is unquestionably from a pleuronectid. By its small size (1.8 mm long), we presume that it is from a juvenile, but this is not necessarily so. In any event, because it is worn and because there is only one specimen, it would not be prudent to speculate as to its generic affinity.

### Cynoglossidae

(Tonguefishes)

*Symphurus* species (Figure 4G): Robins et al. (1980) list 11 species of *Symphurus* as inhabiting waters off the Atlantic and Gulf coastal states; but since we have seen otoliths of only two of these (*S. diomedianus* and *S. plagiusa*), it is impossible to speculate as to the specific affinity of the fossils. The 11 Lee Creek Mine otoliths range in length from 1.0 to 2.6 mm; the figured specimen is 2.6 mm long. *Symphurus* otoliths have been

reported from the Pleistocene of California (Fitch, 1970:35) and from the Miocene of Trinidad; but this is the first record from the Pliocene of North America. Tonguefish otoliths were also present at Day's Point and Rice's Pit.

### Agonidae?

One Lee Creek Mine otolith (3.6 mm long) is an enigma (Figure 4H). The sulcus suggests that it is from an agonid, cottid, or stichaeid, but a comparison with sagittae from species in these families that are known to occur in the western North Atlantic, within the area of concern, has brought no enlightenment. The concave outer face, attenuated anterior and posterior ends, ratio of height into length, and position and configuration of the sulcus will suffice to distinguish this otolith. Should its living congener turn up, we suggest that it will be an agonid.

## Discussion

The 8808 Pliocene otoliths from Lee Creek Mine belong to 17 families and represent at least 45 species. The *Prionotus* and *Citharichthys* otoliths could have represented three species each, but we made no attempt to differentiate these. Ophidiids and sciaenids were the most speciose, with seven kinds each. Other families that were represented by more than one kind of otolith were congrids (5), gadids (5), serranids (4), merlucciids (3), and uranoscopids (2). Based upon our investigations elsewhere, we would anticipate that at least 8 to 10 additional kinds of otoliths could be found in Lee Creek Mine residue if fine-screening techniques, such as described by Fitch (1969c:56–60), were used on another 500 to 1000 pounds of fossiliferous matrix.

Among the 27 kinds of Lee Creek Mine otoliths for which generic names could be assigned, 22 were the first record for the genus in the Pliocene of North America, and of these, 6 represented the first fossil record (Table 1). For one of these, *Lopholatilus chamaeleonticeps*, there was no previous fossil record for the family.

Two kinds of otoliths (*Merlangiogadus* and sciaenid species A, Table 1) are from extinct genera, and there may be other extinct genera among the 13 unnamed otoliths, but decisions on these must wait additional comparative material from extant species. For all but one of the extant genera (i.e., *Pterothrissus*), there are one or more species inhabiting waters off the Atlantic and Gulf coastal states today; however, the nearest living pterothrissid, *P. belloci*, is found in waters off the west coast of Africa.

Because we are generally unfamiliar with the habits and habitat preferences of Atlantic Coast fishes, it would not be prudent for us to state categorically the water depth at the time of deposition of the Lee Creek Mine otolith fauna. Since such an assemblage of fossil otoliths represents a death assemblage only, and there is no first-hand documentation of conditions at the time of their demise, one must draw heavily upon intuition, a knowledge of present-day associations, and suggestions from colleagues, to synthesize any type of paleoecologic conclusion. Wigley and Stinton (1973:33) reported finding otoliths from six of these same species in bottom sediments off Massachusetts, mostly at depths exceeding 100 m. Depths reported for some of the species are: never shallower than about 82 m for *Lopholatilus* (Leim and Scott, 1966:244); 70 to 187 m for *Lepophidium cervinum* (Bigelow and Schroeder, 1953:518); strictly an inshore fish, seldom straying into depths greater than 4 to 6 m for *Microgadus tomcod* (Bigelow and Schroeder, 1953:197); and depths as shallow as 12 meters for *Urophycis tenuis* (Hildebrand and Schroeder, 1928:162). Sciaenids generally range from the intertidal into moderate depths offshore; brotulids and cusk-eels probably overlap at the deep end of the sciaenid distribution and range from there into depths exceeding 200 m; and congrids probably overlap the ophidiids and range into even greater depths.

With the exception of *Ceratoscopelus* and *Merluccius albidus*, all of the otoliths from Lee Creek Mine to which generic names could be assigned were from fishes that inhabit waters shallower than 200 m or they would not have been listed by Robins et al. (1980). Poll (1953:16–21,257)

gives depth distribution data for *Pterothrissus*. The finding of *Ceratoscopelus* otoliths is not unusual, since it is the rule rather than the exception to find myctophid otoliths in fossil faunas comprised of shallow- to moderate-depth species (Fitch, 1969a:1, 17). Presumably the presence of *Merluccius albidus* otoliths presents no more of an enigma than do those of myctophids. The three most abundant kinds, *Lepophidium* (5740 otoliths), *Merluccius* (1086 otoliths), and sciaenid species A (930 otoliths), comprise 88 percent of the recovered otoliths, and even though the recovery techniques (i.e., mostly gleaned by eye in the field) smack strongly of bias toward large otoliths, these three kinds provide the best index for speculating about depth at time of deposition. Based upon all the evidence at hand plus a large amount of intuition, a fauna such as this should represent deposition at 60 to 100 m, but could in fact have been much shallower or a great deal deeper.

This manuscript was completed in April 1973, and during the next 8 years it was updated as new or pertinent information became available. Our presentation contains whatever up-to-date information we felt was pertinent. There is a good chance, however, that we have missed some vital bit of information, or have failed to correct a statement made obsolete during the past eight years. We hope we will be forgiven if such oversights are found—they are not intentional.

The untimely death on 30 September 1982 of the senior author of this report has precluded full revision. The John E. Fitch Collection of fossils, including his notes, correspondence, and library, has been donated to the Natural History Museum of Los Angeles County.

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